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Optimization of the joint startup of the boom and load hoisting mechanisms of a jib crane

Abstract. During the joint motion of the boom and load hoisting mechanisms, dynamic loads increase, leading to additional energy consumption, which subsequently contributes to the deterioration of the crane's structure. The aim of the research was to enhance the efficiency of the jib crane by optimising the joint startup modes of the boom and load hoisting mechanisms, which will minimise energy consumption. To achieve this aim, methods of analytical mechanics, variational calculus, and a modified particle swarm optimisation metaheuristic method were used. As a result of using these methods, the joint startup of the boom and load hoisting mechanisms was optimised. The joint motion of the crane mechanisms is represented by a dynamic model with four degrees of freedom, which accounts for the main motion of the mechanisms, as well as the elastic oscillations of the load hoisting mechanism's drive and low-frequency oscillations of the load on a flexible suspension. Based on the dynamic model, a mathematical model in the form of a system of second-order

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differential equations was constructed, which was then reduced to a system of two fourth-order equations. The synthesis of the optimal startup mode of the mechanisms was carried out according to the criterion of the root mean square value of the total power of the drives, taking into account the constraints on the driving torques of the drives. The constrained optimisation problem was reduced to an unconstrained optimisation problem by developing a generalised criterion. The nonlinear problem of optimising the joint startup mode for the boom and load hoisting mechanisms of the crane was solved using a modified particle swarm optimisation metaheuristic method. As a result of the optimisation, startup modes for the boom and load hoisting mechanisms were obtained that minimise the total power of the drives and eliminate low- and high-frequency oscillations of the crane's structural elements, which leads to increased reliability and reduced energy consumption. This mode is recommended for use in the control systems of crane boom and load hoisting mechanisms

Keywords: dynamic model; mathematical model; optimisation criterion; nonlinear optimisation problem; energy consumption

INTRODUCTION

To increase the productivity of jib cranes, the movements of the boom and load hoisting mechanisms are combined. During the simultaneous startup of these mechanisms, increased dynamic loads and oscillations arise in the elements of the crane boom system. The greatest undesirable impact of these loads occurs when the boom and load hoisting mechanisms undergo simultaneous transient processes (startup, braking, or speed changes). In this case, spatial oscillations of the load on a flexible suspension increase, leading to higher energy consumption, decreased reliability of the crane boom system, and complications for both operating personnel and crane operators. As a result, the problem of selecting startup modes for the boom and load hoisting mechanisms arises, aiming to minimise dynamic forces and eliminate oscillations in the structural elements and the load on a flexible suspension. The effectiveness of jib cranes depends on the magnitude of the dynamic loads acting on the structural elements and the nature of their variation over time.

Considerable attention has been devoted to the study of the motion dynamics of overhead cranes, including jib cranes. The paper by J. Ye & J. Huang (2023) has been investigated the dynamics of cargo transportation by crane reloaders. In this paper, a dynamic model of a tower crane is developed. An equation for predicting coupled-system frequencies is then presented based on the analytical model. Additionally, a hybrid piecewise smoother is proposed to filter out coupled oscillations among jib deflection, load swing, and load twisting.The authors of the article M.M. Bello *et al*. (2024) present modelling and analysis of the dynamic characteristics of a double-pendulum overhead crane. The analysis of the dynamic characteristics of the crane can be useful for developing efficient controllers. The work by M. Michna *et al*. (2020) is dedicated to modelling the dynamics of the movement of a tower crane when testing the operation of individual crane mechanisms. The study of the motion dynamics of an overhead crane with a new wheel design is the subject of the work by N. Fidrovska *et al*. (2021), where stresses in the crane structure elements are determined. In the work by R. Miranda-Colorado (2021), an anti-sway observer for 2D crane systems during hoisting and lowering of loads has been developed. In the work by T. Yang *et al*. (2020), adaptive control against the swinging of a ship crane with roll movements has been implemented based on the developed neural network. The study by R. Buczkowski & B. Żyliński (2021) demonstrates that reducing dynamic loads and swinging of the load on a flexible suspension increases the reliability of jib cranes. Dynamic loads and swinging of the load on a flexible suspension also affect its positioning accuracy during loading, unloading, and assembly operations (Kovalenko *et al*., 2023). During the simultaneous operation of drive mechanisms, dynamic loads in the structural elements and the drives of jib cranes significantly increase. In the scientific work by O. Podoliak *et al*. (2021), modelling and investigation of the dynamics of the combined motion of the mechanisms for load hoisting, changing its outreach and rotation have been carried out. The dynamics of a double-jib crane with a nonlinear PID (proportional-integral-derivative) control system were investigated in a study by N. Sun *et al.* (2019).

The analysis of the conducted research shows that considerable attention has been devoted to studying the dynamics of overhead cranes and the methods of their control. Consequently, these issues remain relevant and require further investigation, particularly concerning the combined motion of the boom and load hoisting mechanisms.

Based on the above, this research aimed to enhance the efficiency of the crane's boom and load hoisting mechanisms by optimising the operational modes of the drive mechanisms. This optimisation minimises the impact of dynamic loads and energy consumption while also reducing high-frequency oscillations of the structural elements and pendulum oscillations of the load on a flexible suspension.

MATERIALS AND METHODS

The joint operation of the boom and load hoisting mechanisms of a jib crane was represented by a discrete dynamic model (Fig. 1). In this model, the boom 1 was represented as an absolutely rigid link that rotated about the lower hinge with a moment of inertia J_1 relative to the rotation axis. It was driven by a hydraulic cylinder 2, which generated the torque M_1 about its axis of rotation. The hoisting of load 3, with the mass m, was carried out by a hoisting mechanism drive, which was reduced to the drive drum 4 with the moment of inertia of the model J_2. A rope with a stiffness coefficient c of a single tackle 5 with n multiplicity is wound onto drum 4 at one end and attached to the boom head at the other.

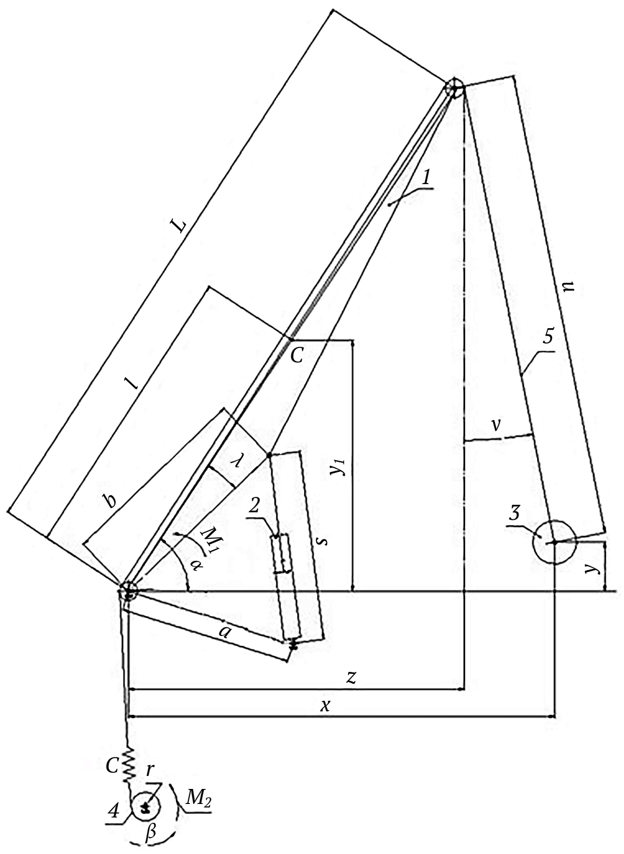

Figure 1. Dynamic model of a jib crane

Note: 1 – boom, 2 – hydraulic cylinder, 3 – load, 4 – drive drum, 5 – single tackle, x – generalised coordinate of the load outreach, z – horizontal coordinate of the boom outreach, y – vertical coordinate of the load position, y_1 – vertical coordinate of the boom's centre of mass, s – working length of the hydraulic cylinder, b, λ – length of the strut from the lower hinge of the boom to the axis of the hydraulic cylinder's rod attachment and its inclination relative to the boom axis, a – length of the strut from the lower hinge of the boom to the axis of the hydraulic cylinder's rod attachment and its inclination relative to the boom axis, u – length of the flexible load suspension, c – centre of mass of the boom, α – angular coordinate of the boom rotation, β – angular coordinate of the drum rotation, L – boom length, l – position of the centre of mass of a boom relative to its lower hinge, v angular coordinate of the deviation of the load on a flexible suspension from the vertical, r – radius of the drive drum of the load hoisting mechanism, M_1 – driving torque of the boom hoisting mechanism, M_2 – driving torque of the load hoisting mechanism

Source: compiled by the authors

The provided dynamic model of the combined motion of the boom and load hoisting mechanisms was represented as a mechanical system with four degrees of freedom. The generalised coordinates of this system were taken as the angular coordinates of the boom rotation α and the drum rotation β, as well as the linear coordinates of the length of the flexible suspension of the load u and its outreach x.

The angular coordinate of the load deviation from the vertical was determined by the following expression:

$$v = \frac{x - L\cos\alpha}{u}, \tag{1}$$

where L – the boom length.

The vertical coordinates of the centres of mass of the boom and the load were also determined:

$$y_1 = l \cdot sin\alpha, \tag{2}$$

$$y = \mathrm{L} \cdot sin\alpha - u \cdot cosv, \tag{3}$$

where l – the position of the centre of mass of a boom relative to its lower hinge.

To construct a mathematical model of the combined motion of the boom and load hoisting mechanisms, second-order Lagrangian equations were used:

$$\begin{gathered} \frac{d}{dt}\cdot\frac{\partial T}{\partial\dot{\alpha}} - \frac{\partial T}{\partial\alpha} = M_1 - \frac{\partial\Pi}{\partial\alpha}, \ \frac{d}{dt}\cdot\frac{\partial T}{\partial\dot{\beta}} - \frac{\partial T}{\partial\beta} = M_2 - \frac{\partial\Pi}{\partial\beta}, \\ \frac{d}{dt}\cdot\frac{\partial T}{\partial\dot{u}} - \frac{\partial T}{\partial u} = -\frac{\partial\Pi}{\partial u}, \ \frac{d}{dt}\cdot\frac{\partial T}{\partial\dot{x}} - \frac{\partial T}{\partial x} = -\frac{\partial\Pi}{\partial x}. \end{gathered} \tag{4}$$

Here T, Π – the kinetic and potential energy, respectively. These were defined as follows:

$$T = \frac{1}{2}J_1\dot{\alpha}^2 + \frac{1}{2}J_2\dot{\beta}^2 + \frac{1}{2}m(\dot{u}^2 + \dot{x}^2), \tag{5}$$

$$\begin{gathered} \Pi = \frac{1}{2}c(\beta\cdot r - (u_0 - u)n)^2 + \\ +(m_1 l + mL)g\cdot sin\,\alpha - m\cdot g\cdot u\cdot cos\,v. \end{gathered} \tag{6}$$

Here m_1 – the mass of a boom; g – the acceleration due to gravity; u_0 – the length of a flexible load suspension at the beginning of the movement; v – the angular coordinate of a flexible load suspension's deviation from the vertical; r – the radius of the drive drum of the load hoisting mechanism. Taking the derivatives of expressions (5) and (6), according to system (4), the following results were obtained:

$$\frac{dT}{d\alpha} = \frac{\partial T}{\partial\beta} = \frac{\partial T}{\partial u} = \frac{\partial T}{\partial x} = 0, \tag{7}$$

$$\frac{dT}{d\dot{\alpha}} = J_1\dot{\alpha}, \ \frac{dT}{d\dot{\beta}} = J_2\dot{\beta}, \ \frac{dT}{d\dot{u}} = m\cdot\dot{u}, \ \frac{dT}{d\dot{x}} = m\cdot\dot{x}, \tag{8}$$

$$\frac{d}{dt}\frac{\partial T}{\partial\dot{\alpha}} = J_1\ddot{\alpha}, \ \frac{d}{dt}\frac{\partial T}{\partial\dot{\phi}} = J_2\ddot{\beta}, \ \frac{d}{dt}\cdot\frac{\partial T}{\partial\dot{u}} = m\cdot\ddot{u}, \ \frac{d}{dt}\cdot\frac{\partial T}{\partial\dot{x}} = m\cdot\ddot{x}, \tag{9}$$

$$\frac{\partial\Pi}{\partial\alpha} = (m_1 l + mL)g\cos\alpha + mgu\frac{\partial v}{\partial\alpha}\sin v, \tag{10}$$

$$\frac{\partial\Pi}{\partial\beta} = c\cdot r(\beta\cdot r - (u_0 - u)n), \tag{11}$$

$$\frac{\partial\Pi}{\partial u} = c\cdot n(\beta\cdot r - (u_0 - u)n) - mg(\cos v - u\frac{\partial v}{\partial u}\sin v), \tag{12}$$

$$\frac{\partial\Pi}{\partial x} = mgu\frac{\partial v}{\partial x}\sin v. \tag{13}$$

Taking into account that the angular deviation coordinate of the flexible suspension of the load v did not exceed 12 degrees, it was assumed that $\sin v = v$ and $\cos v = 1$. Furthermore, the following substitution was made:

$$p = x - L\cos\alpha. \qquad (14)$$

Based on the above and considering dependency (1) and its derivatives the generalised coordinates, expressions (10), (12), and (13) took the following forms:

$$\frac{\partial \Pi}{\partial \alpha} = ((m_1 l + mL)\cos\alpha + mL\frac{p}{u}\sin\alpha)g, \qquad (15)$$

$$\frac{\partial \Pi}{\partial u} = cn(\beta r - (u_0 - u)n) - mg\left(\frac{p^2}{u^2} + 1\right), \qquad (16)$$

$$\frac{\partial \Pi}{\partial x} = mg\frac{p}{u}. \qquad (17)$$

As a result of substituting expressions (7), (9), (11), (14)-(17) into the system (4), the differential equations governing the combined motion of the boom and load hoisting mechanisms were obtained:

$$\begin{gathered} J_1\ddot{\alpha} = M_1 - ((m_1 l + mL)\cos\alpha + mL\frac{p}{u}\sin\alpha)g, \\ J_2\ddot{\beta} = M_2 - cr(\beta r - (u_0 - u)n), \\ m\ddot{u} = -cn(\beta r - (u_0 - u)n) - mg\left(\frac{p^2}{u^2} + 1\right), \\ \ddot{x} = -g\frac{p}{u}. \end{gathered} \qquad (18)$$

When the boom and load hoisting mechanisms are started up simultaneously, dynamic loads in the structural elements and drive mechanisms increase, causing the load to swing on a flexible suspension. In addition, the crane's structural elements are worn, and energy consumption by the drives is also increasing. All of this leads to a decrease in the crane's operational efficiency. Therefore, there was a need to optimise the joint startup modes of the boom and load hoisting mechanisms to minimise energy consumption.

As the criterion for optimising the startup mode of the mechanisms, the root means square value of the total power of the boom and load hoisting drives during the startup process was used. The following dependency represented it:

$$P_{ck} = \left[\frac{1}{t_1}\int_0^{t_1}\{(M_1\dot{\alpha})^2 + (M_2\dot{\beta})^2\}\ \ dt\right]^{1/2} \to min. \qquad (19)$$

The criterion (18), represented as an integral functional, needed to be minimised under the following boundary conditions of starting up the rotation mechanisms:

$$\begin{gathered} t = 0:\ \ \alpha = \alpha_0,\ \ \dot{\alpha} = 0,\ \ \beta = \frac{mg}{cnr}, \\ \dot{\beta} = 0,\ \ u = u_0,\ \ \dot{u} = 0,\ \ x = x_0,\ \ \dot{x} = 0, \end{gathered} \qquad (20)$$

$$\begin{gathered} t = t_1:\ \alpha = \alpha_0 + \frac{\omega_1 t_1}{2},\ \dot{\alpha} = \omega_1,\ \beta = \frac{mg}{cnr} + \frac{\omega_2 t_1}{2}, \\ \dot{\beta} = \omega_2,\ u = u_0 - \frac{v_2 t_1}{2},\ \dot{u} = v_2,\ x = x_0 - \frac{v_1 t_1}{2},\ \dot{x} = v_1, \end{gathered} \qquad (21)$$

where t – the time coordinate; t_1 – the duration of the simultaneous startup of the boom and load hoisting mechanisms; ω_1, ω_2 – the steady-state angular velocities of the boom and the drive drum of the load hoisting mechanism; α_0, x_0 – the initial positions of the boom and the load outreach, v_1, v_2 – steady-state velocities of the load outreach and load hoisting, respectively.

The constraints on the driving torques M_1 and M_2 of the boom and load hoisting mechanisms were defined by the following conditions:

$$M_{1max} \leqslant M_1 \leqslant M_{1max}, \qquad (22)$$

$$M_{2max} \leqslant M_2 \leqslant M_{2max}, \qquad (23)$$

where M_{1min}, M_{1max} – the minimum and maximum allowable values of the drive torque of the boom hoisting mechanism; M_{2min}, M_{2max} – the minimum and maximum allowable values of the drive torque of the load hoisting mechanism.

In the optimisation problem (18)-(23), it was necessary to find the modes of joint startup of the boom and load hoisting mechanisms of a jib crane that minimised the criterion (19) and satisfied the boundary conditions (20) and (21), as well as the constraints (22) and (23).

The criterion (19) was expressed as a function of the generalised coordinates of the boom hoisting α and the change in the load outreach x. To achieve this, the drive torques of the boom and load hoisting mechanisms were expressed using the first and second equations of the system (17):

$$M_1 = J_1\ddot{\alpha} + ((m_1 l + mL)\cos\alpha + mL\frac{p}{u}\sin\alpha)g, \qquad (24)$$

$$M_2 = J_2\ddot{\beta} + cr(\beta r - (u_0 - u)n). \qquad (25)$$

From the last equation of system (18), the deviation coordinate of the load from the vertical in the plane of the outreach change was expressed:

$$p = -\frac{u\cdot\ddot{x}}{g}. \qquad (26)$$

Taking into account the expression (14), the following was obtained:

$$\cos\alpha = \frac{x-p}{L};\quad \sin\alpha = \sqrt{1 - [(x\ -\ p)/L]^2}. \qquad (27)$$

From the first dependency in expressions (27), the generalized coordinate of the boom rotation was expressed:

$$\alpha = arccos\frac{(x-p)}{L}. \qquad (28)$$

By taking time derivatives of expression (28), the angular velocity and acceleration of the boom were obtained:

$$\dot{\alpha} = -\frac{\dot{x}-\dot{p}}{L\cdot sin\alpha},\ \ddot{\alpha} = -\frac{1}{L}\cdot\frac{(\ddot{x}-\ddot{p})\sin\alpha-(\dot{x}-\dot{p})\dot{\alpha}\cos\alpha}{(\sin\alpha)^2}, \qquad (29)$$

dependence (29) included time derivatives of expression (26), which were determined as follows:

$$\dot{p} = -\frac{\dot{u}\cdot\ddot{x}+u\cdot\dddot{x}}{g},\ \ddot{p} = -\frac{\ddot{u}\cdot\ddot{x}+2\cdot\dot{u}\cdot\dddot{x}+u\cdot\overset{IV}{x}}{g}. \qquad (30)$$

additionally, from the penultimate equation of system (18), the angular coordinate of the drum drive mechanism for load hoisting was expressed as follows:

$$\beta = \frac{n}{r}(u_0 - u) + \frac{m}{c \cdot n \cdot r}\left[g\left(\frac{p^2}{u^2} + 1\right) - \ddot{u}\right]. \tag{31}$$

By taking the first- and second-time derivatives of equation (31), the angular velocity and acceleration of the drum drive mechanism for load hoisting were found:

$$\dot{\beta} = -\frac{n}{r}\dot{u} + \frac{m}{c \cdot n \cdot r}\left[2\frac{g}{u^3}p(u\dot{p} - \dot{u}p) - \dddot{u}\right], \tag{32}$$

$$\ddot{\beta} = -\frac{n}{r}\ddot{u} + \frac{m}{c \cdot n \cdot r}\left\{2\frac{g}{u^4}\left[\dot{p}\ \ (u \cdot \dot{p} - \dot{u} \cdot p) + p\ \ (u \cdot \ddot{p} - \ddot{u} \cdot p) - 3 \cdot \dot{u} \cdot p\ \ (u \cdot \dot{p} - \dot{u} \cdot p) - \overset{IV}{u}\right]\right\}. \tag{33}$$

As a result of substituting expressions (14) and (26)-(33) into the dependencies (24) and (25), the functions of the driving moments of the boom and load hoisting mechanisms were obtained. These functions depend on the linear generalised coordinates of the load outreach change x and the length of the flexible load suspension u, as well as on their time derivatives.

To account for the constraints on the driving torques (22) and (23) in the stated optimisation problem, the following dimensionless generalized criterion was introduced and needed to be minimised:

$$Cr = \frac{P_{ck}}{P_{st}} + \delta_P(P_1 + P_2 + P_3 + P_4), \tag{34}$$

where δ_P – the penalty coefficient that accounts for the importance of satisfying the constraints (22) and (23); P_{st} – the steady-state value of the total power of the drives of both mechanisms. To account for the constraints, penalty functions were constructed:

$$P_1 = \begin{cases} 0, if M_1 \geq M_{1\,min}; \\ \frac{M_1}{M_{1\,max}}, if\ M_1 < M_{1\,min}; \end{cases}$$

$$P_2 = \begin{cases} 0, if M_1 \leq M_{1\,max}; \\ \frac{M_1}{M_{1\,max}}, if\ M_1 > M_{1\,max}; \end{cases}$$

$$P_3 = \begin{cases} 0, if M_2 \geq M_{2\,min}; \\ \frac{M_2}{M_{2\,max}}, if\ M_2 < M_{2\,min}; \end{cases}$$

$$P_4 = \begin{cases} 0, if\ M_2 \leq M_{2\,max}; \\ \frac{M_2}{M_{2\,max}}, if\ M_2 > M_{2\,max}. \end{cases} \tag{35}$$

The value of the penalty coefficient $\delta_P = 10^8$ was chosen so that the optimisation algorithm first found a solution that satisfied all the constraints (22) and (23) (thereby reducing all the penalty functions to zero) and then found solutions that gradually reduced the integral functional (19). From the expression (35), it was evident that all terms of the generalized criterion (34) were dimensionless. The first term corresponded to the value of the criterion (19) relative to the steady-state value of the total power of the drives of both mechanisms (i.e., when $t > t_1$), while the second term ensured compliance with the constraints (22) and (23).

The boundary conditions (20) and (21) were expressed in terms of the generalised coordinates of the length of the flexible load suspension and the change in its outreach x, and their time derivatives were determined.

$$t = 0: u = u_0, \dot{u} = 0, \ddot{u} = 0, \dddot{u} = 0, x = x_0, \dot{x} = 0, \ddot{x} = 0, \dddot{x} = 0, \tag{36}$$

$$t = t_1: u = u_0 - \frac{v^2 t_1}{2}, \dot{u} = v_2, \ddot{u} = 0, \dddot{u} = 0,$$
$$x = x_0 - \frac{v_1 t_1}{2}, \dot{x} = v_1, \ddot{x} = 0, \dddot{x} = 0. \tag{37}$$

Here, v_1, v_2 – average steady-state rates of change of the load outreach and the length of its suspension, respectively.

The differential equations of motion (18), the integral functional (19), together with the constraints (22) and (23), expressions (24)-(35), and also the boundary conditions (36) and (37) represent an optimisation problem.

In this problem, it was necessary to determine the control action of the changes in the linear coordinates of the load outreach x and the length of its suspension u, which minimised the value of the criterion (19) and ensured compliance with the constraints (22), (23), as well as the boundary conditions (36) and (37).

The presented optimisation problem was nonlinear, which required the use of an approximate method to solve it. The solutions to the optimisation problem were represented by the unknown functions $u(t)$ and $x(t)$ in the form of polynomials with two terms:

$$u(t) = u_1(t) + u_2(t), \tag{38}$$

$$x(t) = x_1(t) + x_2(t). \tag{39}$$

In the equations (38) and (39), the first terms $u_1(t)$ and $x_1(t)$ were the selected polynomials that satisfied the boundary conditions (36) and (37), while the second terms $u_2(t)$ and $x_2(t)$ were the polynomials that contained free unknown coefficients and provided the following zero boundary conditions:

$$u_2(0) = \dot{u}_2(0) = \ddot{u}(0) = \dddot{u}(0) = u_2(t_1) = \dot{u}_2(t_1) = \ddot{u}_2(t_1) = \dddot{u}_2(t_1) = 0, \tag{40}$$

$$x_2(0) = \dot{x}_2(0) = \ddot{x}_2(0) = \dddot{x}_2(0) = x_2(t_1) = \dot{x}_2(t_1) = \ddot{x}_2(t_1) = \dddot{x}_2(t_1) = 0. \tag{41}$$

The function $u_1(t)$ was represented as a seventh-order polynomial, which allowed for the satisfaction of the first part of the boundary conditions (36) and (37).

$$u_1(t) = \sum_{i=0}^{7} c_i t^i. \tag{42}$$

The function $x_1(t)$ was also represented as a seventh-order polynomial, which allowed for satisfying the second part of the boundary conditions (36) and (37).

$$x_1(t)=\sum_{k=0}^{7}c_k t^k. \quad (43)$$

In the boundary conditions (36) and (37), the time derivatives of the functions $u(t)$ and $x(t)$ were of the third order, that is why they were taken from the functions (42) and (43):

$$\dot{u}_1(t)=A_1+2A_2t+3A_3t^2+4A_4t^3+5A_5t^4+6A_6t^5+7A_7t^6, \quad (44)$$

$$\ddot{u}_1(t)=2A_2+6A_3t+12A_4t^2+20A_5t^3+30A_6t^4+42A_7t^5, \quad (45)$$

$$\dddot{u}_1(t)=6A_3+24A_4t+60A_5t^2+120A_6t^3+210A_7t^4, \quad (46)$$

$$W\dot{x}_1(t)=C_1+2C_2t+3C_3t^2+4C_4t^3+5C_5t_4+6C_6t^5+7C_7t^6, \quad (47)$$

$$\ddot{x}_1(t)=2C_2+6C_3t+12C_4t^2+20C_5t_3+30C_6t^4+42C_7t^5, \quad (48)$$

$$\dddot{x}_1(t)=6C_3+24C_4t+60C_5t^2+120C_6t^3+210C_7t^4. \quad (49)$$

Here, $A_0, A_1, \ldots, A_7, C_0, C_1, \ldots, C_7$ constants that are determined by the boundary conditions of the motion (36) and (37).

After substituting the boundary conditions (36) and (37) into the expressions (42) and (44)-(46), the following results were obtained:

$$A_0=u_0;\ A_1=0;\ A_2=0;\ A_3=0. \quad (50)$$

The constants A_4-A_7 were determined from the following system of linear equations:

$$\begin{aligned} A_4+A_5t_1+A_6t_1^2+A_7t_1^3&=-\tfrac{v_2}{2t_1^3},\\ 4A_4+5A_5t_1+6A_6t_1^2+7A_7t_1^3&=\tfrac{v_2}{t_1^3},\\ 6A_4+10A_5t_1+15A_6t_1^2+21A_7t_1^3&=0,\\ 4A_4+10A_5t_1+20A_6t_1^2+35A_7t_1^3&=0. \end{aligned} \quad (51)$$

After substituting the boundary conditions (36) and (37) into expressions (43) and (47)-(49), the following were obtained:

$$C_0=x_0;\ C_1=C_2=C_3=0. \quad (52)$$

The constants $C_4, \ldots, C_7$ were determined from the following system of linear algebraic equations:

$$\begin{aligned} C_4+C_5t_1+C_6t_1^2+C_7t_1^3&=-\tfrac{v_1}{2t_1^3},\\ 4C_4+5C_5t_1+6C_6t_1^2+7C_7t_1^3&=\tfrac{v_1}{t_1^3},\\ 6C_4+10C_5t_1+15C_6t_1^2+21C_7t_1^3&=0,\\ 4C_4+10C_5t_1+20C_6t_1^2+35C_7t_1^3&=0. \end{aligned} \quad (53)$$

As a result of substituting the constants from (50) and (52), as well as the solutions of the systems of linear algebraic equations (51) and (53), into expressions (42) and (43), the functions obtained, that satisfied the boundary conditions (36) and (37) for the coordinates u and x and their time derivatives.

The polynomials $u_2(t)$ and $x_2(t)$ represented by the following expressions:

$$u_2(t)=\left(\frac{t}{t_1}\right)^4\left(\frac{t_1-t}{t_1}\right)^4\sum_{j=0}^{p}B_j\left(\frac{t}{t_1}\right)^j\frac{v_2t_1}{2}, 0\le t\le t_1, \quad (54)$$

$$x_2(t)=\left(\frac{t}{t_1}\right)^4\left(\frac{t_1-t}{t_1}\right)^4\sum_{k=0}^{n}D_k\left(\frac{t}{t_1}\right)^k\frac{v_1t_1}{2}, 0\le t\le t_1, \quad (55)$$

where $B_0, B_1, \ldots, B_p, D_0, D_1, \ldots, D_n$ – free coefficients that determine the value of the optimization criterion (19); $\left(\frac{t}{t_1}\right)^4\left(\frac{t_1-t}{t_1}\right)^4$ – a multiplier that ensures the zero boundary conditions (40) and (41) are met at arbitrary values of the coefficients $B_0, B_1, \ldots, B_p$ and $D_0, D_1, \ldots, D_n$. These coefficients are free and ensure the determination of the minimum value of the criterion (19).

After substituting the expressions (46)-(54) into the dependencies (38) and (39), and taking into account the boundary conditions (40) and (41), the expressions for the functions $u(t)$ and $x(t)$ were obtained, which included the unknown free coefficients $B_0, B_1, \ldots, B_p$, and $D_0, D_1, \ldots, D_n$.

Using the expressions (28), (29), and (31)-(33), and considering the dependencies (26), (27), and (30), the angular coordinates of the boom rotation and the drive drum of the load hoisting mechanism, as well as their time derivatives were determined, these also depended on the free coefficients $B_0, B_1, \ldots, B_p, D_0, D_1, \ldots, D_n$. When integrating the criterion (19), it also became a function with the free coefficients $B_0, B_1, \ldots, B_p$, and $D_0, D_1, \ldots, D_n$. Thus, the approximate solution to the optimisation problem (18)-(23) was reduced to finding the minimum of the optimisation criterion (19) as a function with the many free coefficients $B_0, B_1, \ldots, B_p, D_0, D_1, \ldots, D_n$.

In order to solve the formulated optimisation problem, the Ring-Rot-PSO metaheuristic method developed by Y. Romasevych *et al*. (2022) was applied.

The number of iterations was set to 50, and the number of particles to 20. In this case, taking into account the expression (19) and the constraints (35), the generalized optimisation criterion (34) was expressed as a function of 10 free coefficients:

$$C_r=C_r(B_0, B_1, \ldots, B_4, D_0, D_1, \ldots, D_4). \quad (56)$$

Calculations for the optimal modes of joint startup of the boom and load hoisting mechanisms were performed based on the root mean square criterion of the total power of the drives (19) and the constraints on the driving moments (22) and (23), and with ensuring the boundary conditions (20) and (21) for the following values of the boom system parameters: $m=4500$ kg, $m_1=2700$ kg, $J_1=72900$ kg·m², $J_2=1183$ kg·m², $C=6.25\cdot10^6$ Nm/rad, $L=9.0$ m, $l=4.0$ m, $v_1=-0.3$ m/s, $\omega_1=0.0396$ rad/s, $v_2=-0.15$ m/s, $\omega_2=2.885$ rad/s, $u_0=8.0$ m, $n=4$, $t_1=5.0$ s, $g=9.81$ m/s², $M_{1\min}=0$, $M_{1\max}=130$ kNm, $M_{2min}=0$, $M_{2max}=4.0$ kNm, $\alpha_0=0.5857$ rad, $x_0=7.5$ m, $r=0.208$ m, $P_{st}=27000$ W.

RESULTS AND DISCUSSION

As a result of solving the optimisation problem, the following values of the free coefficients were obtained: $B_0=6.9513$, $B_1=-5.11235$, $B_2=-13.0874$, $B_3=33.0285$, $D_0=-2.63782$, $D_1=0.829784$, $D_2=-9.80721$, $D_3=12.1441$. The results of applying the *VCP-PSO* method are shown in Figure 2.

Figure 2 shows that, during the operation of the optimisation algorithm, the first four iterations correspond to the penalty functions (35), which account for exceeding the maximum drive torques. Afterward, the algorithm finds a solution that satisfies one of the constraints (35), and during the subsequent iterations (from the fifth to the thirty-first), no significant improvements in terms of the value of the criterion *Cr* can be observed. However, on the thirty-second iteration, the *VCP-PSO* algorithm finds a solution that satisfies all the constraints (35). The subsequent iterations of the algorithm proceed in the region where all the constraints are satisfied, focusing solely on minimising the integral part (19) of the criterion C_r. Such a construction of the objective function (34) allows for a gradual approach to solving the problem: first ensuring the constraints (35), and then minimising the value of the integral functional (19).

Based on the obtained solution to the optimisation problem for the startup process of the boom and load hoisting mechanisms of a jib crane, the graphical dependencies of kinematic, dynamic, and energy characteristics have been built.

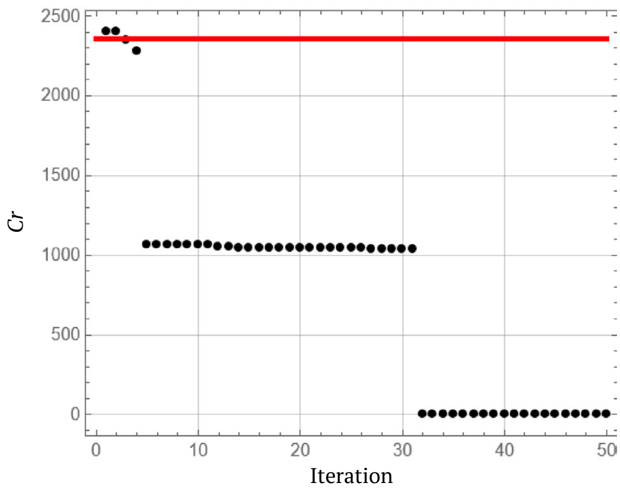

Figure 2. Plots of the decrease of the Cr criterion during the execution of the VCP-PSO algorithm iterations
Source: compiled by the authors

From Figure 3, can be seen that the angular velocity of the boom during startup, both in the baseline and in the optimal calculations, has a similar change pattern. It varies in an oscillatory mode. At the same time, the amplitude of velocity oscillations in the baseline calculation is slightly smaller. The oscillatory nature of the change in the angular velocity of the boom is caused by the nonlinear function of the boom position and the variable function of the static resistance forces acting on the boom.

At the same time, the angular velocity of the drive drum of the load hoisting mechanism changes smoothly during startup (Fig. 4). Such a change is observed both in the baseline and in the optimal calculations for the simultaneous motion of the boom and load hoisting mechanisms. The smooth change in the velocity of the drive drum is related to the fact that its position function is linear, while the static resistance force (the weight of the load) remains constant.

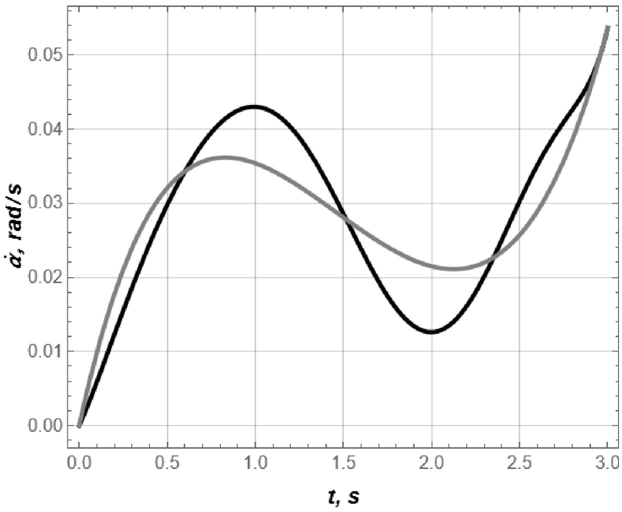

Figure 3. Plots of the angular velocity of boom rotation
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

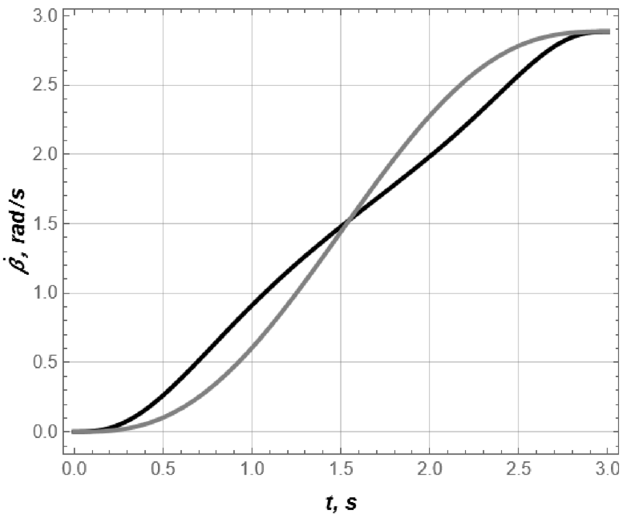

Figure 4. Plots of the angular velocity of the drive drum of a load hoisting mechanism
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

The phase portrait of rope oscillations of a load hoisting mechanism (Fig. 5) shows that the elastic oscillations of the rope damp out within one cycle of oscillation, both in the baseline and in the optimal calculations. However, in the optimal calculation, the deformation of the rope is slightly less and the maximum deformation rate is higher. Moreover, it should be noted that in the baseline calculation, the phase portrait of oscillations changes smoothly, which cannot be said about the phase portrait of oscillations in the optimal calculation, which has a more complex change. This is because the optimal calculation takes into account the actual loads on the structure and the existing constraints, whereas the baseline calculation only considers the boundary movement conditions of the system.

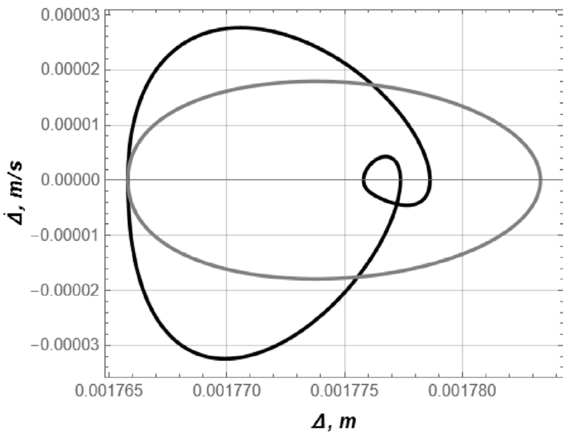

Figure 5. Phase portrait of elastic oscillations of the rope of a load hoisting mechanism
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

The phase portrait of the load oscillations on a flexible suspension (Fig. 6) shows that load oscillations damp out within one cycle, both in the baseline and optimal calculations of the system. However, in the optimal calculation, slightly larger maximum deviations from the vertical of the flexible suspension of the load are observed.

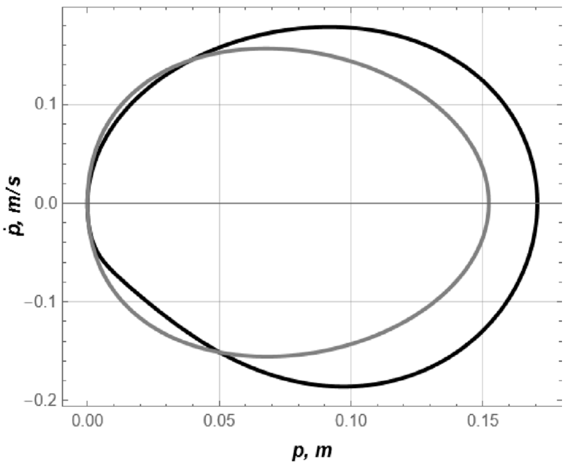

Figure 6. Phase portrait of pendulum oscillations of the load on a flexible suspension
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

In addition, to visualise the fulfilment of constraints (22)-(23) for the optimal solution to the problem, Figure 7 and 8 show the maximum constraints (dashed lines) of the drive torques of the mechanisms for boom and load hoisting. The drive torque of a boom hoisting mechanism (Fig. 7) decreases during startup from its maximum to a steady value, both in the baseline and optimal calculations. However, in the baseline calculation, the drive torque changes smoothly, while in the optimal calculation, it changes in an oscillatory manner. This is due to the fact that in the baseline calculation, there are no constraints on the permissible torque of 130 kNm, while in the optimal calculation, there is a constraint on the maximum value of the drive torque. A similar pattern is observed in the drive torque changes of the load hoisting mechanism (Fig. 8). In the baseline calculation, the torque changes smoothly but does not meet the established limit of 4000 Nm. At the same time, the optimal calculation ensures the torque constraint, but it changes with minor oscillations.

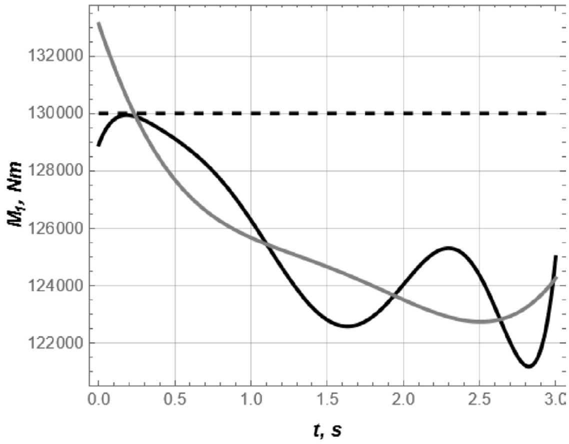

Figure 7. Plots of the drive torque of a boom hoisting mechanism
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

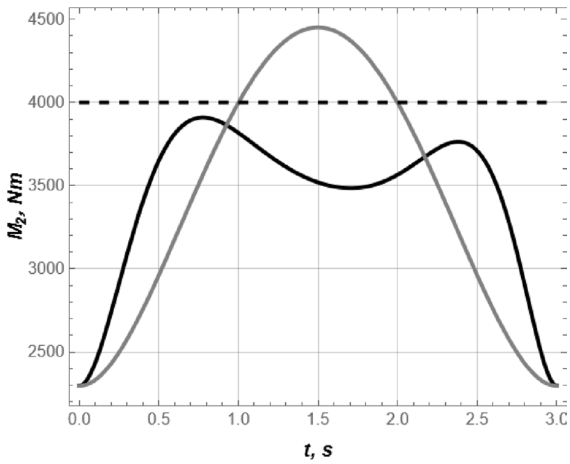

Figure 8. Plots of the drive torque of a load hoisting mechanism
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

The nature of the power change of the drive of a boom hoisting mechanism (Fig. 9) is similar in the baseline and optimal calculations. In both cases, oscillations are observed during the power change, but the amplitude of these oscillations is slightly higher in the optimal calculation compared to the baseline calculation.

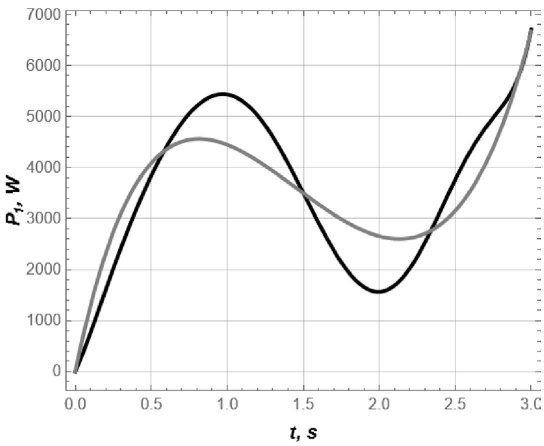

Figure 9. Plots of the power of the drive of a boom hoisting mechanism
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

The drive power of a load hoisting mechanism (Fig. 10) changes from zero to the steady-state value quite smoothly, both in the baseline and optimal calculations. At the same time, in the optimal calculation, the maximum power value slightly exceeds the same value in the baseline calculation.

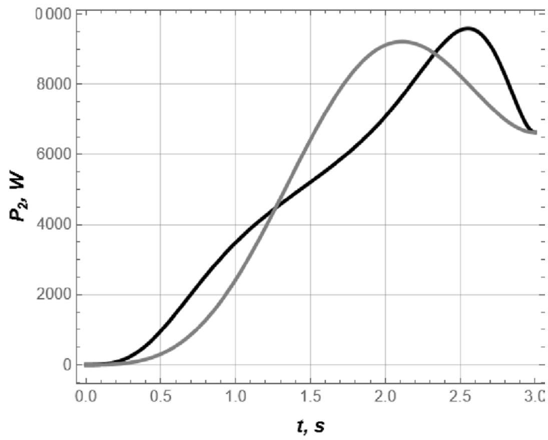

Figure 10. Plots of the drive power of a load hoisting mechanism
Note: the grey curves represent the baseline solution of the problem, and the black curves denote the optimal solution
Source: compiled by the authors

In addition, several numerical indicators are presented, corresponding to both solutions of the problem when determining the modes of combined motion for the boom and load hoisting mechanisms of a jib crane (Table 1).

Table 1. Numerical values of indicators that correspond to the baseline and optimal solutions of the problem (12)-(15)

Evaluation indicator	Unit of measurement	The value of the indicator obtained for the solution	
		baseline	optimal
Class of root mean square indicators			
Load deviation from the vertical	m	0.09693	0.1008
Elastic deformation of the rope of the load hoisting mechanism	m	0.001775	0.001775
Driving torque of the boom hoisting mechanism	kNm	125.35	125.39
Driving torque of the load hoisting mechanism		3.5263	3.4724
Power of the boom hoisting mechanism	kW	3.7015	3.8634
Power of the load hoisting mechanism		6.0567	5.8577
Class of maximum indicators			
Load deviation from the vertical	m	0.1522	0.1706
Elastic deformation of the rope of the load hoisting mechanism	m	0.001783	0.001778
Driving torque of the boom hoisting mechanism	kNm	133.12	129.94
Driving torque of the load hoisting mechanism		4.4509	3.9090
Power of the boom hoisting mechanism	kW	6.6636	6.7026
Power of the load hoisting mechanism		9.2141	9.5834

Source: compiled by the authors

The analysis of Table 1 shows that the indicators for assessing the performance of a jib crane in the baseline and optimal calculations are generally quite close. At the same time, some of these indicators differ from each other in both directions. A more detailed analysis of the obtained indicators is conducted.

The load deviation from the vertical by the root mean square value is 3.8% lower in the baseline calculation than in the optimal one. However, the maximum value of this indicator in the baseline calculation is just 0.2% higher. The elastic deformation of the rope of the hoisting mechanism is the same in both calculations in terms of the root mean square value, and the maximum value of this indicator is 10.8% better in the baseline calculation. The driving torque of the boom hoisting mechanism in terms of the root mean square value, is almost the same in both the baseline and optimal calculations, at 125.4 kNm. However, the maximum value of this indicator is 2.4% lower in the optimal calculation. The driving torque of the load hoisting mechanism, both in terms of the root mean square and the maximum values, decreases by 1.6% and 13.9%, respectively, in the optimal calculation compared to the baseline calculation.

The power of the boom hoisting mechanism, in terms of the root mean square value and the maximum value, is 4.7% and 0.6% less, respectively, in the baseline calculation compared to the optimal calculation. The power of the load hoisting mechanism in terms of the root mean square value, is 3.4% lower and, in terms of the maximum value, is 4.0% higher in the optimal calculation than in the baseline calculation.

An additional analysis of scientific works has been conducted to compare the research results. Consequently, in the article by S.M. Fasih *et al.* (2020), the control of the load slewing mechanism is achieved using a neural network to generate the input data for a jib crane. In the work by A. Kostikov *et al*. (2019), control was implemented by manipulating the length of a flexible suspension to reduce load oscillations during jib crane movement. S. Tong *et al*. (2024) proposed a method for controlling the dynamic sliding mode and developed a dynamic model of a double-pendulum cable crane that considers wind disturbance. The authors of the article by Y. Qian *et al*. (2022) developed a method for controlling the movement of jib crane mechanisms. The work by F. Lui *et al.* (2021) carried out analysing the dynamic and vibration features of a tower crane. The results indicated that mass has little effect on the spatial swing angle, with lifting acceleration remaining stable between 0.004 m/s^2 and 0.01 m/s^2. In the work by R. Čápková & A. Kozáková (2019) considered identifying a dynamic model and designing a controller for changing the trolley position along the arm, as well as damping payload oscillation.

A considerable amount of work was devoted to optimisation of the parameters and motion modes of crane mechanisms has a significant impact on minimising dynamic loads. To solve these problems, metaheuristic optimisation methods by A.P. Piotrowski *et al*. (2020) have been widely applied. The main achievements of optimisation using swarm intelligence methods are presented in the works of other studies (Isiet & Gadala 2020; Houssein *et al*., 2021; Shami *et al*., 2022). The global optimisation of crane mechanism corrections has been investigated in the work by S. Chwastek (2023), based on the fundamental principles of mechanics. Also, a scientific article by S. Chwastek (2020) presented the optimised parameters of crane mechanisms, which make it possible to eliminate vibration (high-frequency oscillations) of the structural elements of a jib crane. At the same time, no restrictions were imposed on the driving forces of the drive mechanisms, meaning that the problem of unconstrained optimisation was solved. In the presented article, high-frequency oscillations of the load hoisting mechanism are also eliminated, but the constraints on the driving forces of drives of the boom and load hoisting mechanisms are introduced. Thus, the authors of this article have solved the problem of constrained optimisation, which is more general. Moreover, the authors of the presented article have developed their method for solving constrained optimisation problems for mechanisms and machines. In the paper by O. Podoliak *et al*. (2021), mathematical modelling of the dynamics of the combined motion of the mechanisms for load hoisting, changing the outreach and rotating a jib crane has been conducted. However, this work does not contain numerical calculations of the dynamics of the combined motion of the mechanisms under consideration. In the work by V. Loveikin *et al*. (2022), optimisation of the process of starting up the load outreach mechanism has been carried out, taking into account the oscillations of the load on a flexible suspension with a steady crane rotation. As a result of the optimisation, the maximum obtained deviation from the vertical of the flexible suspension is 0.031 rad, and the maximum speed is 0.036 rad/s. In the presented article, when changing the outreach and hoisting of the load, similar indicators are equal to 0.0213 rad and 0.0225 rad/s, respectively. The numerical indicators obtained in the presented article are quite close to those from previous studies. The slight difference between the indicators is because the considered variants of the mechanisms have different steady-state speeds of hoisting and changing the outreach of the load. The results presented in this article and in the articles of other authors lead to the conclusion that the research on the dynamics and optimisation of the motion modes of crane mechanisms is relevant. The results obtained in the article are close, and in some cases slightly better than the results obtained in similar studies.

CONCLUSIONS

To minimise energy consumption in the drive mechanisms for boom and load hoisting of a jib crane with adhering the specified constraints, an optimisation problem has been formulated and solved. In this problem, the optimal startup modes of the boom and load hoisting mechanisms have been found by minimising an integral criterion that satisfies the boundary motion conditions of the system and the constraints on the drive torques of the mechanisms. Since the energy consumption of the boom system of a crane largely depends on the power of the drive mechanisms for boom and load hoisting, the criterion for optimisation has been chosen as the root mean square value of the total power of both drive mechanisms during the combined startup mode. To reduce the loads on the structural elements of a crane and the drive mechanisms, the minimum and maximum values of the drive torques have been considered as constraints. In the formulated optimisation problem, the criterion in the form of the root mean square value of the drive powers, along with the constraints on their drive torques, is expressed as a generalised optimisation criterion. In this problem, the issue of ensuring constraints on the drive torques has been addressed first, and then the problem of minimising the root mean square value of the criterion has been solved. Thus, the constrained optimisation problem has been reduced to an unconstrained optimisation problem.

Since the optimisation problem of finding the operating mode of the joint motion of the boom and load hoisting mechanisms of a crane is nonlinear, it could not be solved analytically. Instead, an approximate method has been applied. The solution to the problem has been sought on the class of polynomial functions. The sought functions of the boom and load hoisting mechanisms are represented as a sum of two polynomials. The first polynomial satisfies the boundary conditions of the motion, and the second includes free coefficients that minimise the generalised optimisation criterion. In the solved optimisation problem, the free coefficients have been determined using a modified metaheuristic method *VCP-PSO*.

The solution to the optimisation problem has made it possible to find the modes of joint startup of the boom and load hoisting mechanisms of a jib crane that minimise the total energy consumption of the drives. These results have been achieved by reducing the maximum value of the driving torque of the load hoisting mechanism by 13.9%.

In the process of optimising the modes of joint startup of the boom and load hoisting mechanisms, two calculation variants have been considered: the baseline one and the optimal one. These are compared with each other and show quite close results in almost all the indicators. It should be noted that the baseline calculation variant provides only boundary conditions of the motion, and the optimal one, in addition to boundary conditions, also provides constraints on the driving forces. Therefore, when choosing a movement mode, priority should be given to the optimal calculation method and the results obtained using this method. In further research on optimising the operating modes of a crane's boom system, it is necessary to consider a dynamic model with variable boom length.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Оптимізація сумісного пуску механізмів підйому стріли та вантажу стрілового крана

Анотація. В процесі сумісного руху механізмів підйому стріли та вантажу зростають динамічні навантаження, які приводять до додаткових витрат енергії, що в подальшому витрачається на руйнування конструкції крана. Мета досліджень полягає в підвищенні ефективності роботи стрілового крану шляхом оптимізації режимів сумісного пуску механізмів підйому стріли та вантажу, яка приводить до мінімізації енергетичних витрат. Для досягнення поставленої мети використані методи аналітичної механіки, варіаційного числення та модифікований метаеврістичний метод рою часточок. В результаті використання наведених методів оптимізовано сумісний пуск механізмів підйому стріли та вантажу. Спільний рух механізмів крана представлено динамічною моделлю з чотирма ступенями вільності, де враховано основний рух механізмів, а також пружні коливання приводу механізму підйому вантажу та низькочастотні коливання вантажу на гнучкому підвісі. На основі динамічної моделі побудовано математичну модель у вигляді системи диференціальних рівнянь другого порядку, яку зведено до системи двох рівнянь четвертого порядку. Синтез оптимального режиму пуску механізмів здійснено за критерієм середньоквадратичного значення сумарної потужності приводів з врахуванням обмежень на рушійні моменти приводів. Поставлена задача умовної оптимізації зведена до задачі безумовної оптимізації шляхом розробки узагальненого критерію. Нелінійну задачу оптимізації режиму спільного пуску кранових механізмів підйому стріли та вантажу розв’язано модифікованим метаеврістичним методом рою часточок. В результаті проведеної оптимізації отримано режими пуску механізмів підйому стріли та вантажу, які мінімізують сумарну потужність приводів і усувають низько та високочастотні коливання елементів конструкції крана. Це приводить до підвищення його надійності та зменшення енергетичних витрат. Такий режим рекомендовано використовувати у системах керування крановими механізмами підйому стріли та вантажу

Ключові слова: динамічна модель; математична модель; критерій оптимізації; нелінійна задача оптимізації; енергетичні витрати

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Structuring the energy balance of territorial communities with local infrastructure assets for combined energy production

Abstract. The structure analysis of the energy balance allows use optimal of available resources and infrastructure to maximize energy production, this is especially important for territorial communities with limited resources. The article was devoted to conduct a statistical analysis of combined energy production from wind-solar power plants and sources of thermal generation as part of a typical system of centralized electricity supply and heat for the territorial community of Smila, Cherkasy region, Ukraine. To promote the use of distributed resources, the concept of a microenergy system (MES) has been proposed and its basic structure with energy production, conversion and storage devices. Based on indeterminacy MES leaded a probability distribution model. The results showed that the MES could integrate different types of energy, such as wind, photovoltaic and gas. Multiple energy cycles were achieved through energy conversion and storage devices, and different energy needs were met. Seasonality imposed significant restrictions on the use of heat power plant on solid

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biofuel (HPP) and biofuel cogeneration gas-piston plant (BCP) in the summer, even without taking into account possible maneuvering modes. The level of losses increased from 19.51% till 40.83%, which leads to an increase in the cost of electricity generation. Average values of the specific cost of electricity on the monthly interval for the selected structure sources (SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW) grew in the summer from 23.63% till 53.37%. At the same time, $F_5^e(Y_L)$ reached the highest value in the non-heating season 0.689. The research can be used for practical purposes in the dispatching of generated electric and thermal energy

Keywords: energy supply of territorial communities; energy balance; micropower system; combined production of electricity and heat

INTRODUCTION

The concept of the energy green transition is related to the decarbonization of energy systems which have traditionally depended on fossil fuels. The formation of the energy policy of territorial communities on the basis of the concept of energy security and environmental protection is a modern global trend to ensure the conditions for sustainable development. At the level of territorial communities, this leads to increased interaction between the production processes of the two main types of energy: electricity and heat (European Directive 2018/2001/EU, 2018).

U.J.J. Hahnel *et al.* (2020) noted known experience in the production of green energy by local cooperatives at the regional level through the establishment of an independent supplier. The creation of a local supplier opens up opportunities to provide consumers with an alternative way of energy supply with further technological reorganization of infrastructure in accordance the development strategy of the territory. Decentralized management of energy resources helps to achieve three main goals: energy production at the local level, investment of community resources in regional sustainable development projects, strengthening the role of end consumers in the economic model of formation of energy independence of the territorial community.

Interest in increasing the energy independence of communities through the use of local alternative fuels and renewable sources draws attention to the creation and improvement of local micropower systems for combined energy production of electricity and heat. Local communities are transforming and striving to move away from the traditional role of passive consumers. E. Ghiani *et al.* (2019) demonstrated the current development of small-scale renewable energy makes it possible to form an environment of active users who are both consumers and producers of energy.

V. Kaplun & V. Osypenko (2020) related the research of the interaction combined energy supply systems at the regional level, taking into account functional interrelation in the production of electricity and heat to cover a demand in the long term. As components, it is proposed to consider the subsystems of electricity and heat production in order to manage energy efficiency. Preliminary results of using the method for estimating the technical and economic achievable levels of local energy supply based on micropower systems with polygeneration are presented.

A comprehensive novel approach is presented in this paper by N. Saeed *et al*. (2024) to revolutionized energy trading within microgrids through integration of blockchain technology and smart contracts. Energy token and demand response contracts in decentralized peer to peer energy trading enhance security, efficiency and transparency in microgrid operation. The proposed research on blockchain based microgrid system presents a promising future scope and few limitations. The paper by M.M. Stojiljkovic (2017) was aimed for solving the scientific problem of managing energy supply costs in the medium and long term by coordinating the processes formation of the energy balance on the basis of heterogeneous sources. Access to modern management technologies in the energy sector at the local level is a prerequisite for solving this complex problem. In order to provide territorial communities with scientific and methodological tools that would meet their priorities and be as close as possible to practical realities, it was substantiated the theoretical foundations of the formation of technological and organizational components of energy supply management at the local level.

According to B.P. Koirala e*t al.* (2016), the creation of decentralized energy supply systems for territorial communities is an important factor in the formation of their energy independence. The priority is the consolidation of combined energy production based on the introduction of heterogeneous sources at the system (centralized) level. From the point of view of technical and economic indicators functioning and using of local biofuels, there are technologies for combined production of heat and electricity at local heat power plants (mini-HPPs on solid biofuels, gas reciprocating stations on biogas, etc.).

The scientific solutions for combined heat and power generation with an assessment of their maneuvering capabilities for operation in the combined local energy production (CEP) system with projected energy supply costs for the end consumer are interested. In the existing district heating systems, there is significant potential for modernizing power generating and increasing their efficiency in general. It is mini-HPPs with high fuel efficiency and the ability to maneuver power in a wide range of loads that will be most in demand given changes in prices for heat and electricity with the support of the stochastic mode RES. In addition, the dispatching of combined energy production to cover the specified load schedules (especially for peak periods) also requires the research of different modes of co-production of heat and electricity, taking into account seasonal changes in load schedules.

The paper was devoted to the statistical analysis of combined energy production in the composition of wind-solar power plants and sources of thermal generation (power plants with gas turbines of combined cycle and cogeneration plants with internal combustion engines on biofuels) in a typical system of centralized electricity and heat supply of a separate territory

MATERIALS AND METHODS

A micropower system with combined energy production of electricity and heat in the form of a local energy node was considered (Fig. 1). The structure of combined heat and power system (CHPS) included local heterogeneous sources (Fig. 2) of the network level: solar power plant (SPP), wind power plant (WPP), heat power plant on solid biofuel (HPP), biofuel cogeneration gas-piston plant (BCP), heat grid (HG) and centralized power supply system (CPSS).

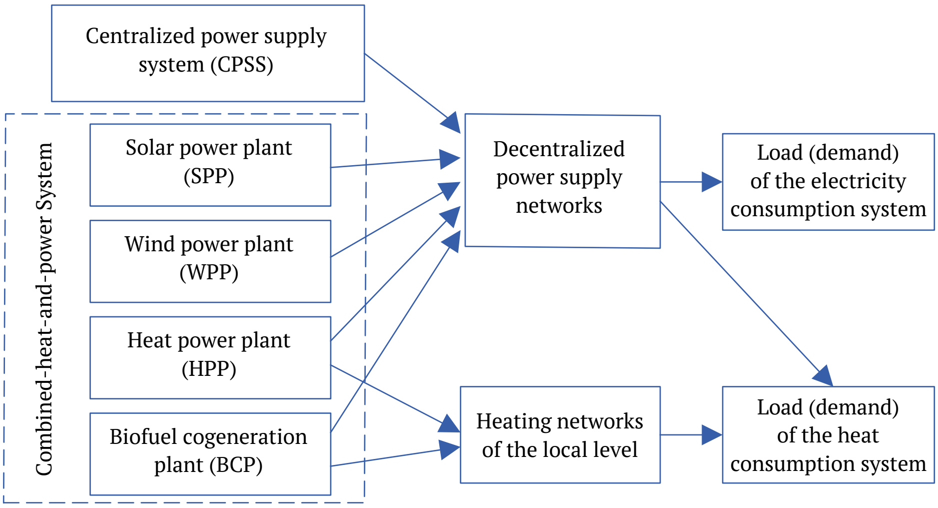

Figure 1. Structure of combined energy supply of the territorial community
Source: compiled by the authors

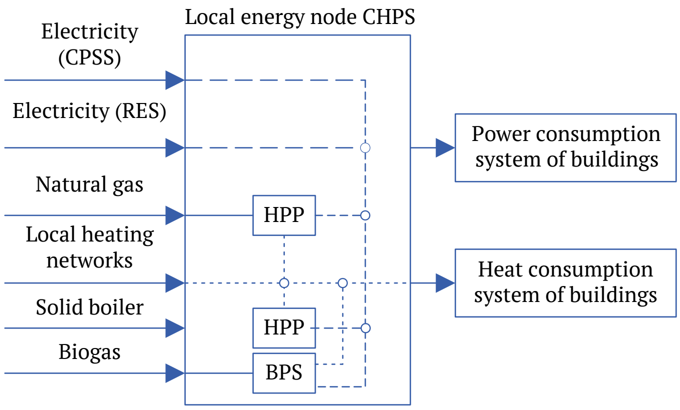

Figure 2. Structure of energy flows of a local CHPS node
Source: compiled by the authors

It was assumed that all energy sources were distributed. Energy streams are transmitted to various end users who were connected to the grid infrastructure. In this case, it considered a homogeneous distributed micropower system, in which each end user has the opportunity to receive energy from all selected sources of the MES in the research time interval $t_{i1} = t_{i2} = \cdots t_{im} = t_i$, everyone $i = \overline{1, n}$.

In the general case, the objective function for *the i-th* technological structure CHPS would look like:

$$min\, obj_i = \sum_{t=1}^{T} g_{SES} \cdot W^e_{SES} + g_{WES} \cdot W^e_{WES} + g^e_{CHPS} \cdot W^e_{CHPS} + g^e_{BCP} \cdot \\ \cdot W^e_{BCP} + g^e_{CPSS} \cdot W^e_{CPSS} + g^h_{HG} \cdot W^h_{HG} + g^h_{CHPS} \cdot W^h_{CHPS} + g^h_{BCP} \cdot W^h_{BCP}, \quad (1)$$

where $g^{e,h}_{*}$ UAH/kWh – unit costs of end users of energy types (e- electrical, h – heat); $W^{e,h}_{*} = P^{e,h} + E \cdot t$, kWh – the amount of energy (electrical and heat) that will be generated in the CHPS to cover the load schedule; $E \cdot t$ – energy of mutual conversion of primary fuels into final types of energy of the user. To calculate the unit costs of electricity and heat in CHPS, it used a simplified calculation according to the formulas (for the first month):

$$g^e_{CHPS} = \frac{A_i+B_i+C_i+D_i}{W^e_i} \cdot \eta^e(\%); \quad (2)$$

$$g^h_{CHPS} = \frac{A_i+B_i+C_i+D_i}{W^h_i} \cdot \eta^h(\%), \quad (3)$$

where A_i – specific capital expenditures attributable to the entire estimated period of operation); B_i – primary fuel consumption for the technological cycle per calendar month; C_i – annual overhead; D_i – unpredictable costs caused by the shutdown of energy production; $\eta_i(\%)$ – coefficient of the basic power of the CHPS unit for the production of electricity and heat in the monthly cycle. Similarly, calculation g^h_{CHPS} was for heat energy.

HPP i BCP – were the aggregate that simultaneously produce electricity and heat in the same production process, also known as cogeneration. The electricity generated was either used locally or fed into a centralized grid, while heat energy could only be used to be discharged into the district heating grid.

The variable range of heat load made it possible to reduce the installed power of the plant to produce the same amount of heat and electricity depending on demand. From the point of view of HPP and BCP technologies, the ratio of electricity to heat (control limits for maneuvering the power of systems) depended on the electrothermal characteristics of the systems.

In general, the balancing of a combined MES to cover the demand for electricity could be as:

$$W^e_{SES}(t) + W^e_{WES}(t) + W^e_{CHPS}(t) + W^e_{BCP}(t) + W^e_{CPSS}(t) = L^e(t) \pm L^e_f(t) + \Delta L^e_{const}(t), \quad (4)$$

where $L^e(t)$ – baseline electrical load (according to the seasonal daily power consumption profile); $\pm L^e_f(t)$ – deviation from the baseline load forecast (the forecast error can be determined by the addition of the study of extended statistical information); $\Delta L^e_{const}(t)$ – the part of the electrical load to cover the heat load (mutual conversion within a combined microgrid system). Similarly, to cover the demand for thermal energy, the determination of the balance from the selected sources would be as follows:

$$W^h_{HG}(t) + W^h_{CHPS}(t) + W^h_{BCP}(t) + W^h_{const}(t) = L^h(t) \pm L^h_f(t). \quad (5)$$

The research was conducted in 2023 on the example of a typical district heating system in the territorial community of Smila, Cherkasy region, Ukraine. The system of combined energy production included a heat power plant with gas turbines operating in a combined cycle, as well as one cogeneration station equipped with internal combustion engines. The study focused on analysing the integration and performance of these systems within the existing infrastructure. The annual electricity consumption is 59214 mWh, heat – 39436 mWh). At the first stage, it was necessary to conduct a retrospective analysis of the nature of energy consumption and justify such a technological structure of CHPS that would cover demand with the lowest cost of electricity production based on available local biofuels TC and RES.

Based on statistical observations and information in Table 1 on real energy production aggregate P6-35/5M (Germany), which operates as part of the regional MES, the initial data for the research were formed.

Table 1. 1. Initial data for modelling the structure of monthly energy balances CHPS

Month	Demand, mW·h	Type of energy: electricity (e); heat (h)	The amount of energy (of the i-th source and its specific cost in the time interval	The type of energy source: SPP	WPP	CHPS	BCP	CPSS	HG	Total cost, ($) and specific costs ($/mW·h) for covering demand
January	6726.02	e	W^e_i	116.04	538.56	2027.86	504.32	3539.24	0	430837.39
			g^e_i	262	85.3	15.26	146.8	70.5	0	64.06
	7898	h	W^h_i	0	0	7108	310.99	0	479.01	174541.49
			g^h_i	0	0	18.15	68.1	0	50.84	22.10
February	7802.05	e	W^e_i	260.1	442.82	1953	498.97	4647.16	0	544309.45
			g^e_i	262	85.3	19.21	146.8	70.5	0	69.76
	9082	h	W^h_i	0	0	3365.38	307.68	0	5408.94	380784.75
			g^h_i	0	0	25.21	68.1	0	50.84	41.93
March	4946.15	e	W^e_i	576.3	626.48	1401.08	478.11	1864.18	0	431848.48
			g^e_i	262	85.3	18.42	146.8	70.5	0	87.31
	6245	h	W^h_i	0	0	2670.91	294.77	0	3279.32	256371.67
			g^h_i	0	0	26.05	68.1	0	50.84	41.05
April	4964.78	e	W^e_i	681.56	644.05	1711.64	490.36	1437.17	0	467163.94
			g^e_i	262	85.3	35.26	146.8	70.5	0	94.10
	2674	h	W^h_i	0	0	1265.88	302.16	0	1105.96	161415.52
			g^h_i	0	0	66.84	68.1	0	50.84	60.36

Continued Table 1.

Month	Demand, mW·h	Type of energy: electricity (e); heat (h)	W_i^e	The type of energy source						Total cost, ($) and specific costs ($/mW·h) for covering demand
				g_i^e	WPP	CHPS	BCP	CPSS	HG	
May	4469.65	e	W_i^e	1075.3	676.92	2063.27	501.52	152.64	0	450986.13
			g_i^e	262	85.3	13.15	146.8	70.5	0	100.90
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
June	4350.27	e	W_i^e	1124.52	418.75	1946.72	488.17	372.11	0	451932.,31
			g_i^e	262	85.3	12.17	146.8	70.5	0	103.89
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
July	4192.11	e	W_i^e	1168.22	432.79	674.95	469.14	1447.01	0	521332.78
			g_i^e	262	85.3	11.05	146.8	70.5	0	124.36
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
August	4234.14	e	W_i^e	924.1	365.94	1337.18	382.98	1223.94	0	429905.25
			g_i^e	262	85.3	10.52	146.8	70.5	0	101.53
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
September	4204.12	e	W_i^e	612.24	584.68	550.68	515.05	1941.47	0	428848.07
			g_i^e	262	85.3	11.05	146.8	70.5	0	102.01
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
October	4873.95	e	W_i^e	473.9	534.36	2289.64	490.13	1085.92	0	344742.29
			g_i^e	262	85.3	11.57	146.8	70.5	0	70,73
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
November	5440.12	e	W_i^e	138.24	232.56	2326.31	479.06	2263.95	0	317209.81
			g_i^e	262	85.3	13.42	146.8	70.5	0	58.31
	6670	h	W_i^h	0	0	5269.08	295.42	0	1105.5	196930.96
			g_i^h	0	0	22.89	68.1	0	50.84	29.52
December	7277.83	e	W_i^e	67.66	658.92	2463.68	505.19	3582.38	0	440194.54
			g_i^e	262	85.3	16.05	146.8	70.5	0	60.48
	10245	h	W_i^h	0	0	9546.95	311.54	0	386.46	256910.98
			g_i^h	0	0	22.63	68.1	0	50.84	25.08

Source: compiled by the authors based on Smila city territorial community (n.d.)

Additional characteristics of mini HPPs: Boiler units – KVGM-20, DKVR-10-39-44 (Ukraine); Turbines – P6-35/5M (Germany) No. 1, 2 with a capacity of 6 MW. To form the technological structure of CHPS, network level sources with installed powers were selected for analysis, namely: SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW.

The scientific idea of the study was the assertion of the possibility of determining the limit levels of the ratio of particles of electric and thermal energy during a given calculation period. This would make it possibility to determine the time periods of participation of homogeneous sources in the formation of optimal energy balances (daily, monthly, annual) of the combined energy supply system with the selected structure of heterogeneous sources and a deterministic load profile.

RESULTS

The using of several local sources that form the structure of CHPS and were integrated into existing centralized networks requires an analysis, namely:

1) determination of annual consumption (demand) and opportunities of the territorial community for the production of biofuels and the power generating capacities in accordance with the Green Deal;

2) research of the structure CHPS energy balance with selected sources to cover demand during the billing period. It was assumed that own energy production should only cover current energy needs. The limitation was that the possibility surplus energy produced in previous periods cannot cover the needs in future periods in which production is insufficient;

3) determination of short-, medium- and long-term energy profiles of CHPS for combined heat and power generation based on a predictive assessment of the cost indicators of energy supply to end users;

4) the formation of energy independence of territorial communities through the integration of several heterogeneous sources of distributed generation of small power requires the justification of certain rules and procedures. The major feature of the construction of such combined energy production systems is their ability to predictably change the structure of the energy balance by replacing the main component of energy consumption from external networks with their own generation. Under certain conditions, CHPS can switch in isolating (island) mode of operation without reducing the quality of power supply. At the same time, synchronization with external grids allows maneuvering distributed generation in the micropower system, taking into account the stochastic parameters of own generation, and having operational flexibility when using sources of local heat generation.

Wide opportunities for variability ratio of electricity and heat production expanded the cost ranges of energy supply for end consumers. The using of multi-unit mini-HPPs provided a fairly wide range of maneuvering load of station, which created the prerequisites for the search for economically justified operational indicators in seasons with medium or low demand for heat production.

Technological opportunities and constraints for the electrical and heat generation in the combined cycle generally is lied in the seasonal demand for final energy (electricity and heat) and access to local primary fuels.

The schematic flow diagram of the combined heat and power generation is shown in Figure 3.

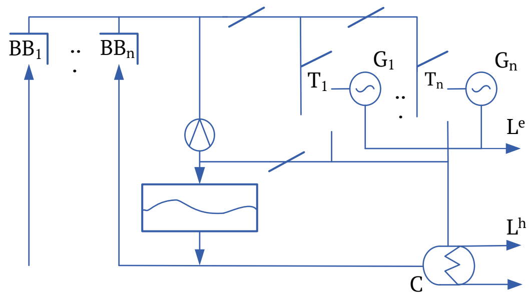

Figure 3. Technological scheme of combined energy production by Heat power plant

Note: BB – solid biofuel boiler, T – turbine, G – generator, C – condenser, L^e – electrical network, L^h – heating network)

Source: compiled by the authors

The graphs of monthly profiles of demand for electricity and heat (Fig. 4) and total costs for energy supply (Fig. 5) of the territorial community city Smila, Cherkasy region, were obtained.

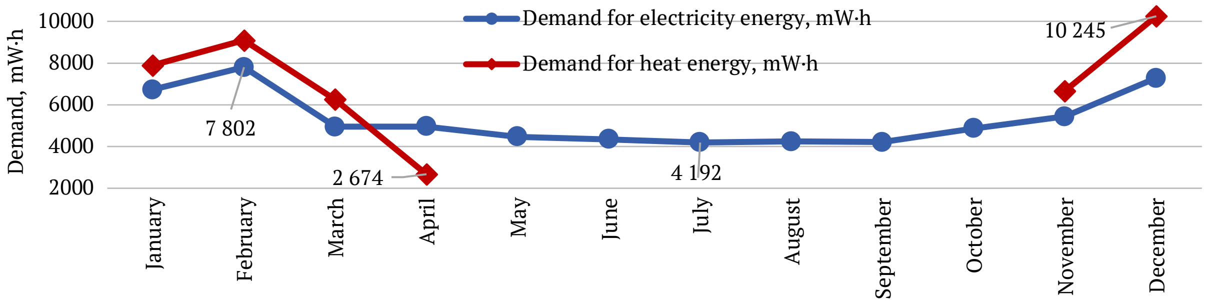

Figure 4. Monthly load profile (demand for electricity and heat energy)

Source: compiled by the authors

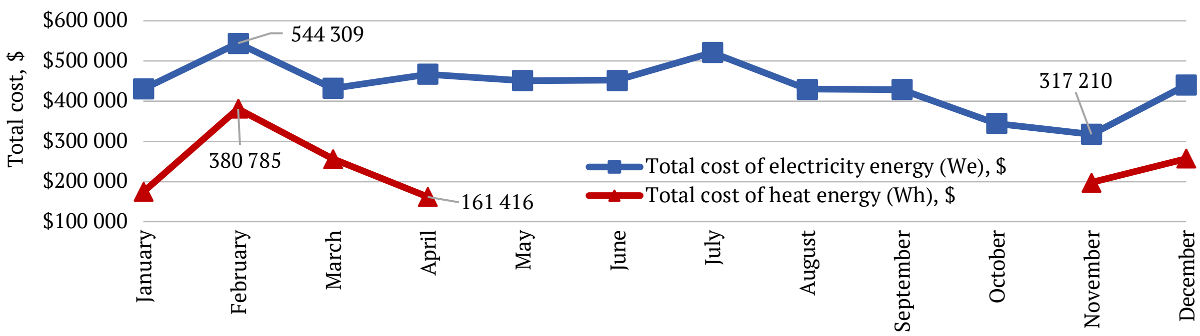

Figure 5. Total monthly energy costs of the territorial community to cover the demand for electricity and heat energy

Source: compiled by the authors

To test the efficiency of proposing structure combined energy supply micro-energy system the values the unit costs of electricity and heat averaging on the monthly interval (Fig. 6) were obtained. It was taken into account the peculiarities of technological cycles of conversion of primary fuels of heat generation sources and the possibility of balancing micro-energy systems from external grid.

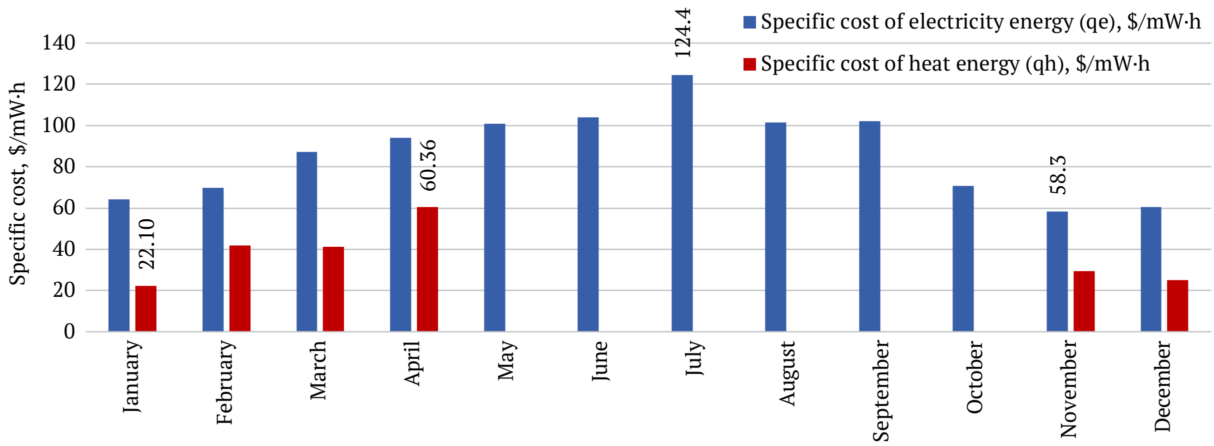

Figure 6. Average values of unit costs of electricity and heat for the structure of sources micro-energy systems with installed power

Note: SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW

Source: compiled by the authors

Combining production of heat and electricity with an assessment of their maneuvering capabilities for operation in the local energy production system make it possible to predict the cost indicators of energy supply for the end consumer, taking into account the efficiency of conversion of primary fuels in sources of heat generation. Figure 7 shows the interrelation between electricity and heat generation, energy losses in HPP and BCP in non-maneuvering mode of operation without taking into account seasonality, when heat recovery does not occur. This mode of operation of heat generation sources is not optimal. It is applied on the bject, where the statistical data are used in research.

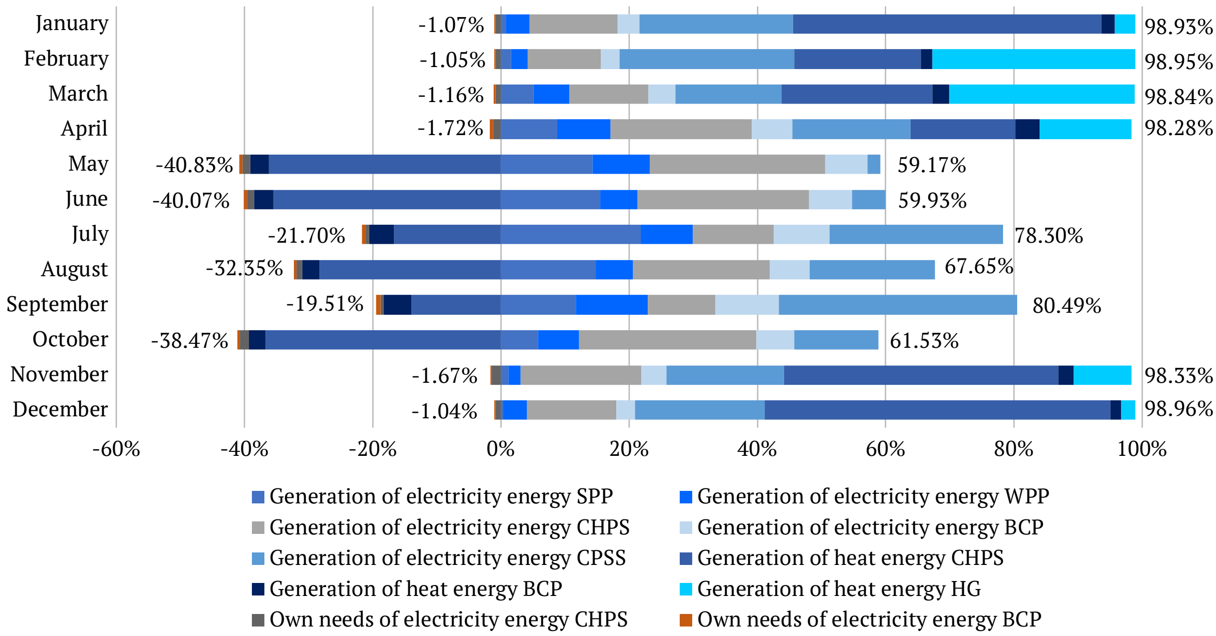

Figure 7. Interrelation between electricity and heat generation, energy losses in HPP and BCP in non-maneuvering mode of operation without taking into account seasonality, when useful heat recovery does not occur

Source: compiled by the authors

To algorithmize the operation of the micro-energy system, taking into account seasonal changes in local generation and demand, it is necessary to determine model series taking into account the provision of the basic part of demand during the calendar year and the response to demand taking into account seasonal changes. At the same time, the formation of MES energy balances with the selected structure of sources should be considered as management efficiency of the system as a whole. Combined energy sources with high fuel efficiency and the ability to maneuver power in a wide range of loads will be the most request a season with demand for heat energy. The demand for electricity (primarily in the summer) should be provide by the generation of wind and solar power plants. Dispatching of combined energy production to cover specified load schedules (especially for peak periods) also requires the research of different modes of co-production heat and electricity energy, taking into account seasonal changes in load schedules.

To analyse the efficiency of structuring a micro-energy system with the selected sources, it was used the approach proposed by V. Kaplun (2023). Let denote the vector of parameters of external factors in the formation of the energy balance $D(t)$ such as the cost of primary fuel, the efficiency of combined energy production technologies, and the interdependence between electricity and heat production in the cogeneration cycle. The structuring vector $R(t)$ includes the structural implementations of micro-energy systems with the stochastic nature of RES (renewable energy sources). The vector of control influences is denoted as $Y(t)$, and the criterion functionality as F_T.

The criterion (goal) functional is integral, since in multicomponent systems, optimal solutions, as a rule, are determined not by the instantaneous reaction of the system, but for a certain calculation period T:

$$F_T = \int_0^T F_i\big(D(t), R(t), Y(t)\big)dt, \quad i = \overline{1, n}. \qquad (6)$$

With this representation (6), the value of the F_T is a function of input parameters and control influences $Y(t)$. Parameters $D(t)$, $R(t)$, $Y(t)$ depend on the season and the selected structure of the sources and their being in the active state (state of generation), are variable and are given by an expression of the type:

$$D_{min} \leqslant D \leqslant D_{max}.$$

Changes in these parameters are also mutually dependent

$$\Delta_t(D(t), R(t), Y(t)) \geqslant 0.$$

To understand the features of the formation of functionality F_T is considering the diagram of electricity, heat generation and technological energy losses related to the sources of heat generation (Fig. 6). Results of functional calculations F_T as the coefficient of imbalance of the selected structure MES in the conditions of deterministic definition of the output data combining production of electricity and heat are given in Table 2.

Table 2. Results of functional calculations F_T

D_i / $Y(t)$	$F_1^{e,h}$	$F_2^{e,h}$	$F_3^{e,h}$	$F_4^{e,h}$	$F_5^{e,h}$	$F_6^{e,h}$	$F_7^{e,h}$	$F_8^{e,h}$	$F_9^{e,h}$	$F_{10}^{e,h}$	$F_{11}^{e,h}$	$F_{12}^{e,h}$
Y^e	0.533	0.608	0.401	0.312	0.038	0.098	0.409	0.328	0.497	0.233	0.421	0.494
Y^h	0.581	0.534	0.411	-	-	-	-	-	-	-	0.166	0.562
Y_L	0.011	0.012	0.011	0.016	0.689	0.668	0.277	0.478	0.242	0.625	0.017	0.011

Source: compiled by the authors

The functionality F_T is calculated Table 1 as an unbalance coefficient for the selected structure of electricity sources (Y^e) and ranges from 0.038 till 0.608, which indicates an insufficient share in the balance of MES solar generation in the summer calendar period, especially for July and August ($F_7^e = 0.409$ та $F_8 = 0.328$). It is foreseeable that the electricity balance will be sufficiently structured in the periods from May to September on the basis of the generation of wind-solar systems with minimal consumption from the centralized CPSS grid.

The heat supply system has a slightly different design of the energy balance of the territorial community. The lack of demand for district heating from April to October imposes restrictions on the use of heat generation with combined energy production, since most of the heat energy cannot be disposed of in the summer. The constancy of the heat consumption schedule requires the operation of heat generation sources at the rated power of HPP and BCP without the use of shunting modes in the periods from November to March. Balancing MES by heat (Y^h) should be carried out at the expense of the heat grid (HG) and local (objects) tools of heat supply. Only in November, the demand for heat energy is provided with sufficient efficiency $F_{11} = 0.409$.

Dispatching of combined energy production to cover specified load schedules (especially for peak periods) requires the research of different modes of co-production heat and electricity energies, taking into account seasonal changes in load schedules. Combined energy supply processes will encourage territorial communities to a new type of activity, which is due to own energy production based on the use of local fuels and renewable energy sources (RES). The outlined approaches can be a theoretical basis for the development scenarios for the formation energy independence of territorial communities.

The dispatching strategy based on the specific value indicators of energy generation opens the way for the maximization of operating income. The priority of balancing the micro-power system to cover the demand is given to WPPs and SPPs, which are highly profitable generating facilities. Optimal cost performance and energy efficiency performance of primary biofuels conversion are key criteria during periods when CHPS and BCP operate in the "heat load determined capacity" mode. It was shown that the results of functional calculations, from which it can be seen that combined energy supply (supply of electricity and heat) can be achieved due to energy complementarity, provided that reducing the cost of energy is the goal of optimization.

The results of the research can be used to develop dynamic energy management systems, which will allow formation tariff plans for end consumers of the territorial community, taking into account combined energy production based on local biofuels, the positive impact of MES of this class on the survivability energy islands in case of an unpredictable decrease in the power of centralized sources, system accidents, blackouts, etc.

M. Bagheri *et al.* (2019) noted the introduction of local energy supply systems for territorial communities is an important factor in gradually increasing their level of energy independence. The priority direction is the fusion of combined energy production through the use of decentralized sources at the system (centralized) and local (on the side of the end consumer) level.

A. Karimi *et al*. (2024) researched that from the point of view technical and economic indicators of the functioning and using local fuels, the technologies, which are combined production heat and electrical energy at regional heat power plants are attractive. New challenges, in territorial communities are mainly associated with the consequences of rising prices in electricity market, as well as the variability of generation resulting from an increasing deal of RES. In many existing district heating systems, there is significant potential for modernizing power generating and improving their efficiency in general. The study suggests a management strategy that involves using a new decentralized controller for the effective organization and coordination of ESSs and RESs to enhance the operation of isolated microgrids. According to M. Bagheri *et al.* (2019) for the combined production of thermal and electrical energy with an assessment of their maneuverability, working in a combined local energy system with predicted specific values of energy supply for the end consumer are solutions of interest. Exactly local heat power plants with high fuel efficiency are able to maneuver power in a wide range of loads. Therefore, they will be the most in demand given the increase in tariffs for heat and electricity with the support of the stochastic mode with RES. In addition, the dispatching of combined energy production to cover the specified load schedules (especially for peak periods) also requires the research of different modes of co-production of heat and electricity, taking into account seasonal changes in load schedules.

L. Mehigan *et al.* (2018) researched the prerequisites for the technical modernization of traditional energy industries, highlighting the challenges that drive the development of innovative energy Internet platforms. X. Zhao *et al.* (2018) explored how micro-energy systems serve as prototypes for object-oriented decentralized microgrids within the energy Internet framework. Their work suggests that these systems could promote the formation of multi-energy and polygenerational energy supply models for territories and communities, emphasizing the use of renewable energy sources and local fuels. In the notable publications by L. Ju *et al.* (2016), research on microgrids is devoted to the coordination of operational planning and the solution of optimization problems aimed at minimizing operating costs and reducing environmental impact. The principles of constructions a dispatching system and the strategy of energy management in the long term are presented in detail. In a paper by K. Fellah & R. Abbou (2024) a layer-like optimization model based on the modes of the regulated thermoelectric cogeneration unit's coefficient is presented. At the first level, the criterion of minimum energy costs was applied, and the second level of efficiency is according for the economic criterion. H.A. Gabbar *et al.* (2015) presented the results of optimizing the functioning of regional networks with minimal energy consumption and environmental impact. The works of G. Guandalini *et al.* (2017) and X. Zhang *et al.* (2018) were dedicated to the introduction of carbon credits as a market commodity using technical and economic indicators (minimum costs for electricity production) and carbon emissions trading on the performance of the system. Photovoltaic modules, energy storage devices and heat exchangers for local load were integrated into the microgrid system, which helped to reduce the cost of electricity generation. These articles did not address the uncertainties associated with the functioning of microgrids with polygeneration. This complicates the understanding formation of energy security levels for such objects. The uncertainty of micropower systems with polygeneration is mainly related to the operation of wind and solar power plants, the lack of use of controlled generating units, energy storage and flexible load for optimal matching of supply and demand. In the research by F.J. Heredia *et al.* (2010), the method of stochastic optimization of electricity generation by a wind-solar station by means of two-level dispatch optimization for virtual power plants is described. J. Li *et al.* (2024) proposed day-ahead scheduling model is a mixed-integer, nonlinear, large-scale, stochastic optimization problem with high dimensional random variables, which is difficult to be solved directly by traditional centralized method. The simulation results show that the proposed distributed optimization algorithm has high accuracy and good convergence, the virtual power plant can achieve day-ahead optimal scheduling and effectively promote renewable energy accommodation under the security and reliability of the grid. The problem of wind consumption based on fast maneuvering control with the help of gas generators has been solved by J. Mohammadi *et al.* (2007), H. Yang *et al.* (2014).

Methods based on stochastic programming optimization are the most common for processing indetermination. However, it is problematic to obtain a probabilistic analysis of the stochastic processes on which stochastic optimization depends. Therefore, optimization procedures are often characterized by boundary parameters of indetermination factors and the selection of a reliable optimum. As a rule, it's a conservative decision. Solving multi-purpose optimization models is also a key problem in microgrids functioning. In general, multi-purpose models are solved with the help of related algorithms, but the introduction of indetermination and several optimization criteria significantly complicates the models and introduces contradictions into the solutions. Solving algorithms mainly incorporate traditional approaches and heuristic intelligent algorithms, which were reviewed by Z.-F. Tan *et al.* (2014). In the first case, problems in defining parameters and transforming constraints are shown, which leads to low optimization effectiveness. In the second case, the best solutions are obtained, but the research and selection of the extremum is carried out without taking into account the principles of multi-purpose programming. Therefore, according to Z.-F. Tan *et al.* (2014), the algorithm stops at the local extremum, which limits the possibility of finding the optimum. As noted by Y.-W. Jiang *et al.* (2008), the solution of the problem dispatching energy flows in a multicomponent system by optimizing particles and algorithms of differential evolution. It shows the solution of the multi-purpose model as the main problem in structure optimal strategies for dispatching micropower systems.

A. Bloess *et al.* (2018) researched that the presence of commonality of modes of combined energy production of electricity and heat is characterized by the fact that the cost of accumulating heat energy is much lower compared to the cost of accumulating electrical energy, which makes the planning and operation of electricity and heat more and more attractive in practical implementation. Coordinated management of energy flows between electricity and heating networks can simultaneously contribute the decarbonization of the heating sector and provide the greater flexibility needed for renewables with indetermination generation. By D. Connolly *et al.* (2014) noted that energy system modelling tools are usually created for the electricity sector, and the potential benefits of local district heating systems are generally overlooked.

Obviously, in order to assess the potential of district heating networks, it is necessary to take into account the availability of local infrastructure and available fuel. As a rule, modelling tools are used that do not take into account the interaction between the processes of combined energy production of electricity and heat. At the same time, it is important to understand that in this case, there are naturally restrictions on the use of tools that would embody a holistic approach, considering both systems as an integrated whole.

CONCLUSIONS

The research focused on the statistical analysis of combined energy production in wind-solar power plants and thermal generation sources (gas turbine power plants in combined cycles and cogeneration plants with biofuel internal combustion engines) within a typical centralized electricity and heat supply system. The territorial community of Smila, Cherkasy region, Ukraine, served as the case study.

The results showed that combined energy production systems with high fuel efficiency and flexible load management are crucial for minimizing heat and electricity costs, especially when dealing with the stochastic nature of Renewable Energy Sources (RES) generation. These systems, including biofuel-based cogeneration plants (BCP) and heat power plants (HPP), face challenges such as increased energy losses during the summer season, where losses rose from 19.51% till 40.83%, leading to higher electricity generation costs. The average specific cost of electricity for the selected energy sources (SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW) increased in the summer from 23.63% till 53.37%. The imbalance coefficient reached its highest value of 0.689 during the non-heating season, indicating significant inefficiencies in the summer months.

From the perspective of electricity demand coverage, thermal generation and, to some extent, wind energy systems are foundational in the energy structure, while solar power contributes to covering morning load peaks during the spring and summer. BCPs act as operational power reserves, ensuring flexibility during both peak demand periods and load decreases.

The study also established that the efficiency of combined heat and electricity generation strongly correlates with the demand for thermal energy, suggesting further research into optimal dispatching strategies. These findings highlight that local energy systems, particularly micro-energy systems (MES), can be more self-sufficient and cost-effective with decentralized power generation.

Future research will explore the development of decentralized microgrids with polygeneration capabilities and short-term load forecasting, providing better energy balancing and reliability. This shift towards energy-independent islands and peer-to-peer energy trading within energy communities will create new opportunities for decentralization, enabling consumers to actively manage their energy use and enhance energy efficiency in local systems.

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CONFLICT OF INTEREST

None.

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Структурування енергетичного балансу територіальних громад з локальними інфраструктурними активами для комбінованого виробництва енергії

Анотація. Аналіз структури енергетичного балансу дозволяє оптимально використовувати наявні ресурси та інфраструктуру для максимізації виробництва енергії, що особливо важливо для територіальних громад з обмеженими ресурсами. Метою статті було проведення статистичного аналізу комбінованого виробництва енергії від вітро-сонячних електростанцій та джерел теплової генерації у складі типової системи централізованого постачання електричної та теплової енергії для територіальної громади міста Сміла, Черкаська область, Україна. Щоб сприяти використанню розподілених ресурсів, запропонована концепція мікроенергетичної системи (МЕС) та її основна структура з пристроями виробництва, перетворення та зберігання енергії. На основі невизначеностей МЕС вводиться модель розподілу ймовірностей. З цілями максимізації операційного доходу та мінімізації операційного ризику та викидів вуглекислого газу було створено багатоцільову скоординовану модель оптимізації диспетчеризації. Результати показують, що МЕС може інтегрувати різні типи енергії, такі як вітер, фотоелектрична енергія та газ. Кілька енергетичних циклів досягається за допомогою пристроїв для перетворення та зберігання енергії, і задовольняються різні потреби в енергії. Сезонність накладає суттєві обмеження на використання теплових електростанцій на твердому біопаливі (ГЕС) та біопаливних когенераційних газопоршневих установок (БГУ) в літній період, навіть без урахування можливих маневрових режимів. Рівень втрат зростає з 19,51% до 40,83%, що призводить до збільшення собівартості виробництва електроенергії. Середні значення питомої собівартості електроенергії на місячному інтервалі для обраної структури джерел (СЕС – 1,0 мВт, ВЕС – 1,6 мВт, ГЕС – 8,5 мВт, БГУ – 1,0 мВт) зростають влітку з 23,63 % до 53,37 %. При цьому $F_5^e(Y_L)$ досягає найбільшого значення в неопалювальний сезон 0,689. Дослідження можуть бути використані у практичних цілях при диспетчеризації генерованої електричної та теплової енергії

Ключові слова: енергозабезпечення територіальних громад; енергетичний баланс; мікроенергосистема; комбіноване виробництво електроенергії і тепла

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Research of the influence of filter element resistance on the powered air-purifying respirator service life

Abstract. The purpose of the research was to determine the influence of the increasing resistance of filter elements on the service life of powered air-purifying respirators during operation in mining conditions and to substantiate the parameters of the respirator power source. The research was conducted by the computer-based simulation methods for the powered air-purifying respirator operation, which allows estimating the additional resistance of the filter caused by dust accumulation. The simulation model of the powered air-purifying respirator was developed on the basis of its physical model and, taking into account the empirical dependence of the change in the filter element resistance during dust deposition, allows determining the flow of air through the filter and the dust aerosol concentration in the working area air. The following parameters of the simulation model of a powered air-purifying respirator were substantiated: controlling action – fan rotating speed, restrictions on air flow and air pressure in the respirator mask (depending on the

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mode of working arrangements of the user), concentration of dust in the air of the working area, capacity of the power source, power consumption of the electric motor of the fan and control system components, parameters of filter elements (fibre packing density, filter layer thickness, fibre diameter, etc.), input concentration of dust aerosol, which made it possible to establish the relationship between the value of the filter element resistance and the time to complete discharge of the power source. A critical value of the resistance of the filter elements of the powered air-purifying respirator was established, which results in a significant discharge of the power source, based on the different flow rate of the air supplied to the undermask space at a given dust concentration in the working area. Relationship between the change in breathing resistance of the filters and the discharge of the power source was established, which allows determining the period of safe operation of the powered air-purifying respirator, based on the concentration of dust in the working area air and the user's working arrangement. The practical value involves determining the lifespan of the powered air-purifying respirator, based on the critical value of the filter resistance, which results in the rapid discharge of the power source

Keywords: controlling action; simulation model; control object; identification; research; air consumption; battery; electricity; duration of operation

INTRODUCTION

The main function of powered respiratory protective devices (hereinafter, powered air-purifying respirators or PAPR) is to protect the user's respiratory organs from inhalation of hazardous aerosols or pathogenic microorganisms which increase the risk of occupational diseases. The efficiency of protection when using PAPR depends on comfort, degree of protection and performance. All three parameters mentioned are largely influenced by the high consumption in the air supply system and the air pressure in the undermask space of the respirator. In turn, the flow rate and air pressure determine the time of the protective action or, in other words, the service life of the PAPR, since the increase in resistance on the filters, caused by the accumulation of a dust layer on their surface, requires an increase in the performance of the fan and results in increasing energy consumption of the battery. It may be frightful to think of a situation when in a remote polluted area, where the necessary production tasks are performed, the battery suddenly discharges and the worker is left without protection. In accordance with the physical load, it is necessary to substantiate the parameters, develop and research the operation of the PAPR control system. To eliminate the negative impact on people during experimental research, it is necessary to use a simulation model of the control system of the PAPR to determine the dependence of the service life on the increasing resistance of its filter elements when used in mining conditions and to determine the parameters of the power source – the battery.

The issue of the duration of the protective effect of powered air-purifying respirators is an urgent research topic in modern science. In particular, C. Forgez *et al*. (2010) focused attention on the issues of rapid discharge of the power source of this personal protective equipment for respiratory organs. One of the factors is the increase in filter resistance, as evidenced by the research of K.T. Strickland *et al*. (2023). They found that with increasing resistance, the load on the system increases, which accelerates energy consumption. E.M. Villanueva & R. Ahmad (2021) studied the effect of frequent changes in the operating mode of the fan, which requires the rotation frequency to be increased, which also affects the lifespan of the battery.

In order to overcome these problems, scientists propose developing new algorithms for controlling the ventilation system. A.P. Collins *et al*. (2021) suggested improved models which allow for smooth transitioning between operating modes, taking into account efficient energy consumption. This is becoming particularly important for prolonging the protective effect of respirators.

A. Licina *et al*. (2020) focused on modelling the operation modes of powered air-purifying respirators, in particular, to determine the duration of the protective action under real operating conditions. However, as noted by A. Kothakonda *et al*. (2021), maintenance of batteries when stored is also an important factor. Without proper maintenance, situations may arise when the level of protection of the respirator does not meet the requirements.

Other researchers, including Z. Xu *et al*. (2020), saw a solution in the development of algorithms for diagnosing the state of the battery taking into account external factors such as temperature and humidity. M. Bergman *et al.* (2019) make suggestions for the use of respirators with a tighter fit to the face so as to reduce air losses, which may contribute to increased service life of the device. M. Bergman *et al*. (2014) emphasise that this solution requires additional checks in production conditions to ensure proper tightness.

S.I. Cheberiachko *et al*. (2023) investigated battery types which could provide maximum lifetime with minimum maintenance costs; however, they noted that the selection of the optimal battery type depends on specific operating conditions. X. Xia *et al*. (2023) drew attention to the necessity to create simulation models which would allow accurate forecasting of energy consumption depending on device operating modes.

As a result of the analysis of the available literary sources, it was found that although the issue of the duration of the protective effect of powered air-purifying respirators is being actively studied, there is still no single agreed strategy to solve it. The purpose of the research is to substantiate the parameters of the simulated model of the PAPR to determine the influence of the increase in the filter element resistance on the service life of the power source when used in mining conditions.

To achieve the set goal, the following tasks are to be completed:

- to develop a simulated model of a powered air-purifying respirator based on its physical model;
- to determine the critical value of the resistance of the filter elements of the PAPR which results in a significant discharge of the power source.

MATERIALS AND METHODS

The PAPR simulation model was developed using the active experimentation method (Edirisooriya & Haas, 2023), which solved the problem of determining the structure and parameters of the mathematical model of the research object in the form of a transfer function equation. For this, a number of one-factor experiments were performed which evaluated the impact on the research object of both individual factors (change in fan rotating speed, change in filter resistance, etc.) and their interaction. Planning and processing of the results obtained during the research were performed using formal methods of mathematical statistics.

To develop a structural diagram of a powered air-purifying respirator as an object of control and to determine the parameters of the PAPR structural elements, the main relationships were established of its constituent elements (Fig. 1), which are different in nature, namely, pneumatic ones (related to the air movement: filter, fan propeller, flexible tube with connected mask, inhalation/exhalation valves) and electrical ones (speed controller and fan motor).

To determine the structure, parameters and algorithm of operation of the air pressure regulator for the control system of the powered air-purifying respirator, a heuristic method was applied, which was based mainly on the erudition and intuition of the designer. Due to the determining of the parameters of the powered air-purifying respirator regulator, the task to increase the efficiency of its operation was solved on the basis of establishing the main relationships between the parameters.

The elements of the control and management system, according to the main characteristics of the PAPR, based on the algorithm of its work, are given in Table 1.

Table 1. Operating procedure, operation and indication sequence in different operating modes of the unit

Operations	Performed actions and running commands
Switching on	When the S1 button is pressed, the power supply voltage is supplied to the microcontroller unit, which is signalled by the HL1 LED. At the same time, the power supply voltage is supplied to the fan from the microcontroller unit (MU). After 7-10 s (the time of setting the nominal air flow rate in the air duct), the signal from the tachometer $f_т$ is sent to the MU, where it is compared with the reference frequency $f_з$ for the nominal flow rate, and if $f_т \geqslant f_з$, the HL2 signal LED is turned on and a one-shot beep sounds; when $f_т \leqslant f_з$ (which may indicate the "triggering" of the anti-aerosol filter), the HL3 signal LED is turned on and short beeps sound; if there is no air flow in the line ($f_т = 0$), the LED HL4 and a continuous beep signal that. The status of the battery is indicated using the HL5 signal LED, which flashes when the remaining battery capacity is at least 25-30%; when the voltage on the battery stack drops to 2.8-3 V, the fan turns off, and the HL5 LED lights up continuously.
Increasing air flow	When the S3 button is pressed from the MU, an increased supply voltage is applied to the fan, which is signalled by the HL6 LED.
Switching off	When the S2 button is pressed, the blower is turned off.
Anti-aerosol filter activation alarm	When the anti-aerosol filter is activated during operation, its aerodynamic resistance increases, as a result of which the air flow in the line decreases; if it is impossible to compensate for it due to the intensification of the fan, the "Warning" signal is first activated (the HL3 signal LED flashes and beeps are emitted), and then, with the filter layer resistance increasing, the "Emergency" signal is activated (the HL3 LED is turned on and a continuous sound is emitted).
Battery discharge alarm	When the remaining capacity of the battery decreases to the level of 25-30%, light (HLX) and sound (HA) intermittent "Warning" signals are activated. The air supply does not stop. When the voltage on the battery stack drops to 2.8-3 V, a continuous sound signal "Accident" is turned on, and after ~10 s the turbo block is turned off!

Source: developed by the authors

According to the PAPR operation algorithm, control of its operation modes, namely: stabilisation of the amount of normalised air flow supplied to the under-mask (under-helmet) space, control and warning of the user with light and sound signals about the "triggering" of the anti-aerosol filter, as well as the autonomous power source (lithium battery), was carried out using an electronic unit whose structural diagram is presented in Figure 2.

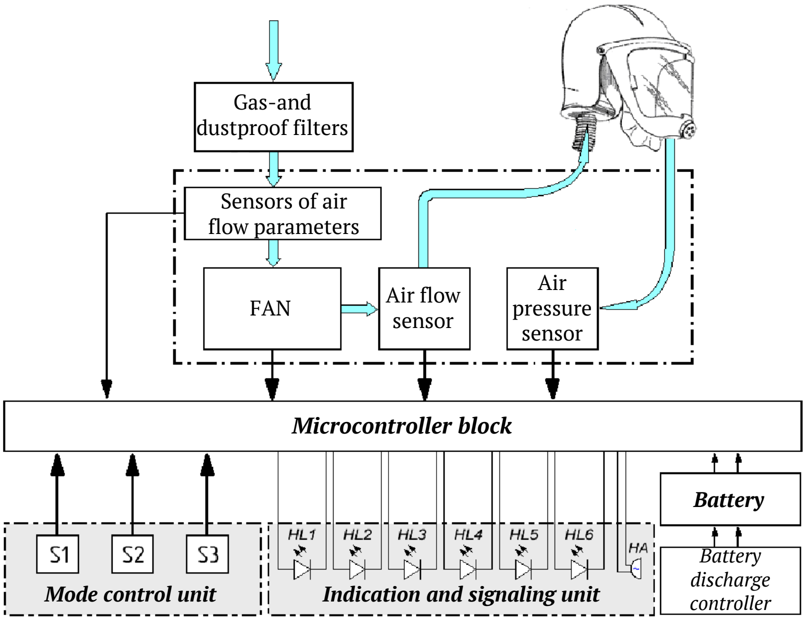


Figure 1. Schematic diagram of the PAPR for the forced purified air supply into the under-mask space

Note: S1-S3 – “On”, “Off” and “Increased air flow” switches, respectively; HL1-HL6 – “On”, “Nominal air flow”, “Replace the filter”, “No air flow”, “Increased air flow” and “Battery discharged” mode indicators, respectively; HA – sound alarm of emergency modes of fan operation

Source: developed by the authors

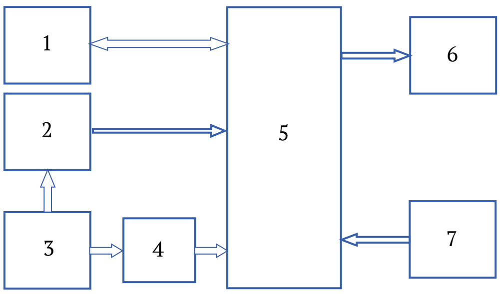


Figure 2. Schematic diagram of the electronic control unit for PAPR operating modes

Note: 1 – flow driver, 2 – control unit, 3 – battery, 4 – battery discharge controller, 5 – process controller unit, 6 – alarm module, 7 – carbon monoxide level control module

Source: eveloped by the authors

The electronic unit consisted of the following main structural elements:

- a mode control unit, which enabled/disabled PAPR and increased air flow mode;
- a unit for controlling the carbon monoxide content in the air inhaled, which provided conversion and amplification of the signal from a special electrochemical sensor (CO module);
- air flow driver, which consisted of a fan and a tachometer. The fan created the required air flow and was controlled by a pulse width modulation (PWM) signal, and the tachometer converted the fan turbine rotation frequency, which is proportional to the volume flow rate, into electrical pulses suitable for further measurement of the flow rate;
- the process controller unit processed the signals coming from the control unit, CO module and tachometer and, in accordance with the established algorithm, performed PWM signalling to control the frequency of rotation of the fan, as well as light and sound indication of various operating modes of the turbo unit;
- the alarm unit generated warning light and sound signals according to the controller’s commands;
- the battery provided power supply to the components of the turbo unit;
- the battery discharge controller was a combination of a voltage indicator with element-by-element control and a controlled electronic key, which made it possible to organise the disconnection of the battery from the load when any of its elements reaches the critical value of 3.2 V.

Implementation of the specified requirements when developing the electronic circuit of the PAPR operating mode control unit is currently possible only with the use of an element base on microcontrollers, i.e. microprocessors with built-in memory devices and other additional functions.

Considering the fact that formation of a gradually growing layer of dust on the filter surface is a peculiarity of the functioning of any individual respiratory protection device, even during the PAPR operation, the increase in the pressure drop across the filter due to the dust accumulation results in an increasing air flow, which necessitated the development/improvement of a simulation model which would take into account this additional resistance to the air flow. At the same time, the amount of dust deposited on the filter was calculated according to the formula (Baek *et al.*, 2024):

$$\Pi_\phi = \frac{2CQt}{F_0}, \quad (1)$$

where C is the total dust concentration, mg/m^3; Q is air flow rate through the filter, m^3/s; t is a time interval of respirator operation, s; F_0 is the total area of the filter, m^2.

The total resistance of the filter was determined based on the equation (Tcharkhtchi *et al.*, 2021):

$$\Delta p_{total} = \Delta p_o + \frac{k_n \rho_n \phi F_0^2}{3\pi^2 L}\left[\left(F_B^2 + \frac{2\Pi_\phi F_B}{a\rho_n \phi F_0}\right)^{3/2} - F_B^3\right], \quad (2)$$

where Δp_0 is the initial resistance of the clean filter, Pa; k_p is the proportionality factor which depends on the filtration rate, m^4/s^2; ρ_d is the bulk density of dust particles, kg/m^3; φ is the coefficient of uneven distribution of dust on material fibres; F_F is the total surface of filter fibres; L is the total length of fibres in the filter, m^{-1} (Tcharkhtchi *et al.*, 2021):

$$L = \frac{\beta \cdot H}{\pi \cdot a^2}, \quad (3)$$

$$F_F = \frac{2\beta H}{a}, \quad (4)$$

where β is fibre packing density; H is the filter layer thickness, m; a is the mean radius of the fibres in the filter, m.

The required battery capacity was calculated according to the formula (Bašić *et al.*, 2023):

$$C = \frac{P \cdot t}{U}, \quad (5)$$

where C is the battery capacity, Ah; P is power consumption, W; t is time, h; U is battery voltage, V.

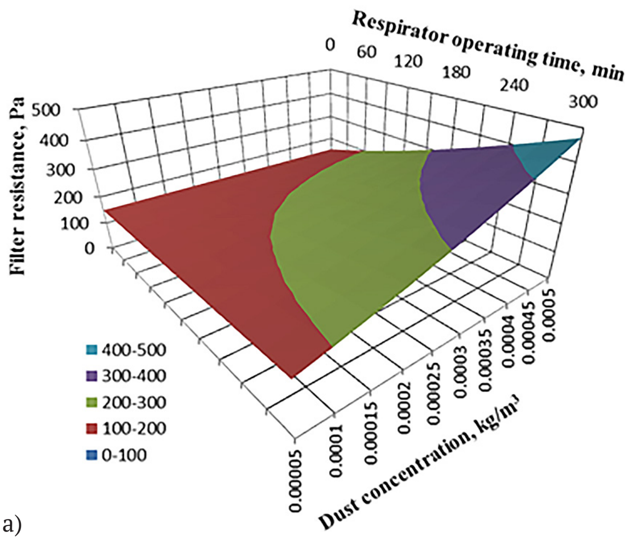
Considering the importance of the effect of additional resistance from dust accumulation on the powered air-purifying respirator operation, it became necessary to calculate the final filter resistance depending on the period of PAPR application, which, in turn, resulted in a rapid depletion of the power source charge.

For example, it was assumed that a work shift at coal enterprises in underground workings lasts six hours, of which the worker was in the dusty zone for about five hours (an hour was arranged for preparing and completing work) (Wu *et al.*, 2020). That is, the active use of the respirator was to be at least 5 hours. At the same time, the concentration of dust in the air varied from 50 to 500 mg/m^3; the volume flow of air varied from 115 to 260 dm^3/min.

Taking into account the fact that the area of the filter membrane of one filter element was 0.005 m^2 (the diameter of the FRPA P2 filter cartridge is 100 mm), the total area of filtration for a respirator with two similar elements was 0.01 m^2. The filtering element, formed into concentric curved folds (corrugations), was made of non-woven material "Eleflen" (Scientific and Production Enterprise "Standard", Ukraine), with a height of the filtering layer of 4-5 mm, a packing density of 1.1, a fibre diameter of 2-3 µm (Bazaluk *et al.*, 2021). The PAPR provided continuous air purification during 1 working shift (up to 5 hours). The final total pressure drop across the filter should not exceed 800 Pa.

RESULTS AND DISCUSSION

The results of calculating the change in filter resistance from the time of PAPR operation according to the method given in the works by M.A. Boraey (2021) and T. Dziubak (2024) with different dust concentrations are presented in Figure 3 – when using 1 filter and Figure 4 – when using 2 filters.



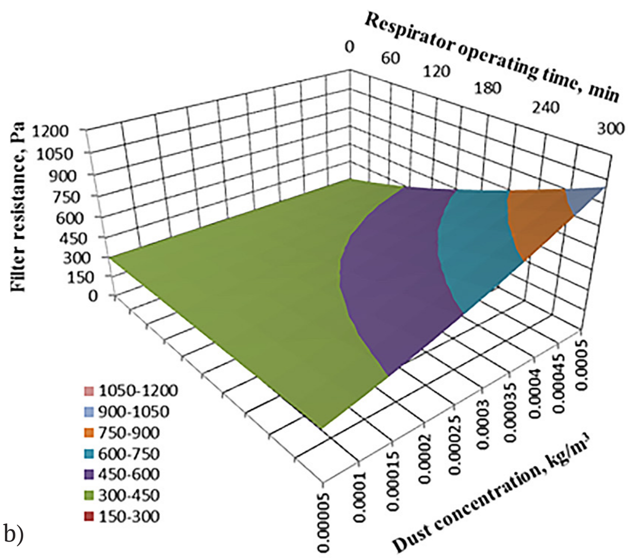


Figure 3. Dependence of the resistance of 1 filter on the operation time and dust concentration
Note: a) air flow rate 140 l/min, b) air flow rate 260 l/min
Source: developed by the authors

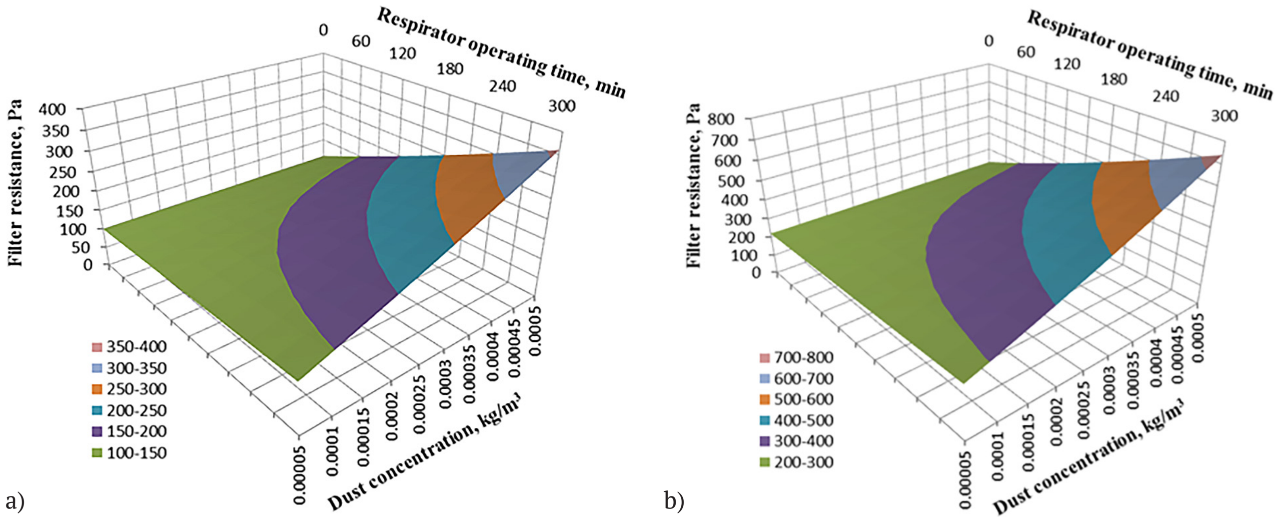


Figure 4. Dependence of the resistance of 2 filters on the operation time and dust concentration
Note: a) air flow rate 140 l/min, b) air flow rate 260 l/min
Source: developed by the authors

This made it possible to plot the dependence of the change in the additional resistance of the filter on the accumulation of dust sediment at maximum air flow and dust concentration relative to the time of operation when using one (Fig. 5, curve 1) and two filters (Fig. 5, curve 2). From this, it was established that in the most unfavourable operating conditions, namely, the maximum dust concentration and the maximum air flow required the total resistance to air movement at the end of the work shift is 1006 Pa when using one filter, exceeding the norm; when two filters are working, it is equal to 736 Pa.If it is necessary to increase the service life of the PAPR, it is essential to use filters with a larger filtering surface.

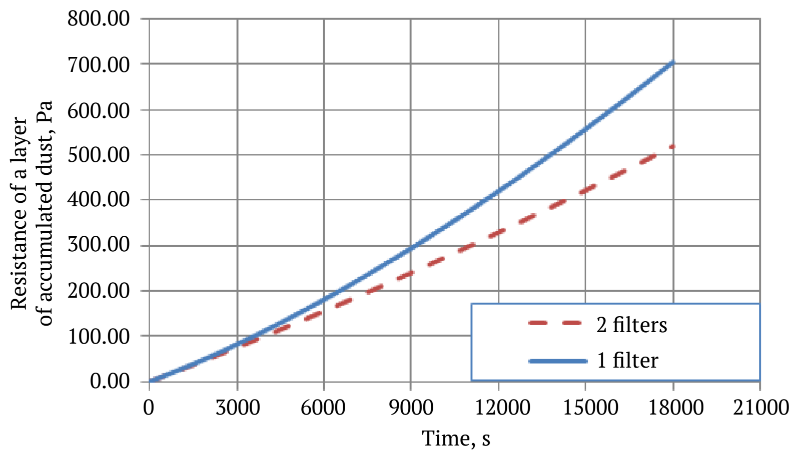


Figure 5. Change in the added resistance of the respirator filter from the time of operation at a flow rate of 260 l/min and a dust concentration of 500 mg/m³ when using one (1) and two filters (2)
Source: developed by the authors

Taking into account the schematic scheme of the electronic control unit, which demonstrates the relationships between various components of the PAPR design, as well as the need to take into account the additional increase in resistance on the filter surface due to dust deposits according to equations (1) and (2), the simulation model, which is presented in Figure 6, was improved (Slavynskyi, 2023). The main parameters of the simulation model included the controlling action – fan rotating speed, restrictions on the maximum additional resistance of the respirator filter, concentration of dust in the air of the working area, parameters of filter elements (fibre packing density, filter layer thickness, fibre diameter and others).

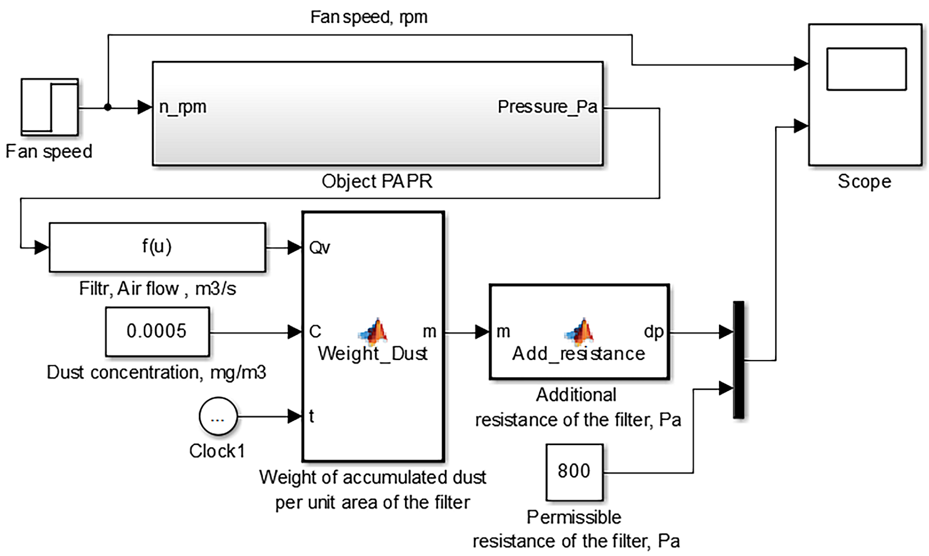


Figure 6. A simulation model with the possibility of calculating the additional resistance of the filter against the dust accumulation
Source: developed by the authors

The results (Fig. 7) of the simulated modelling of the change in the additional resistance of the filter due to the accumulation of the dust layer correspond to the calculated ones (Fig. 5), so the developed functions can be applied in the further research. Verification of the operation of the simulated model of the powered air-purifying respirator, whose structural diagram is presented in Figure 8, under different modes of air supply is shown in Figure 9 as well as when adding the simulated signal "Breathing" (with the scaling of the dust accumulation rate 1:100).

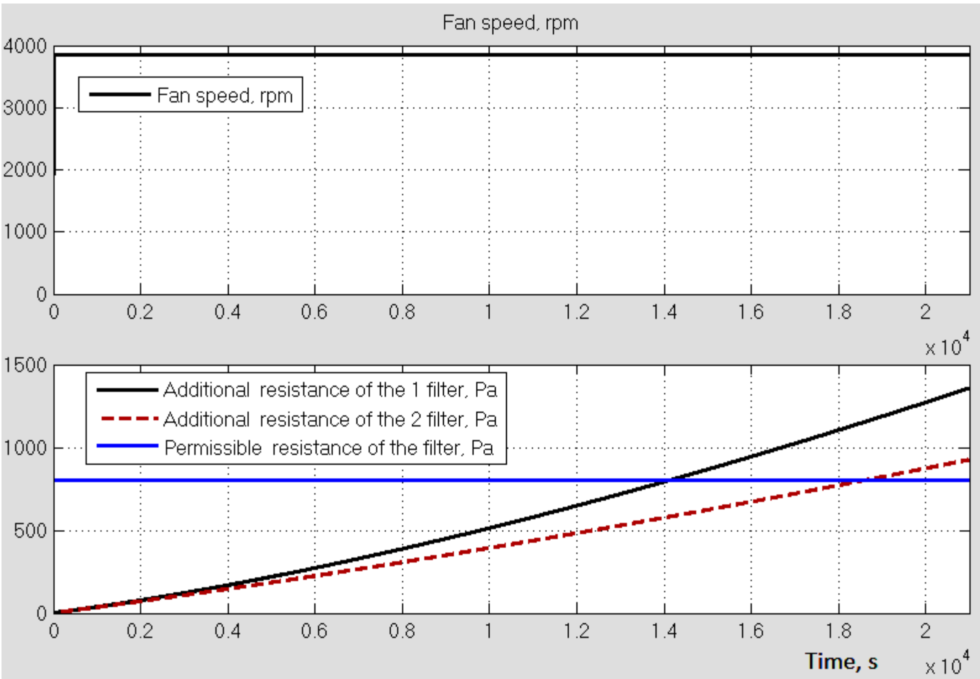


Figure 7. The results of modelling the function of changing the additional resistance of the filter from the dust accumulation
Source: developed by the authors

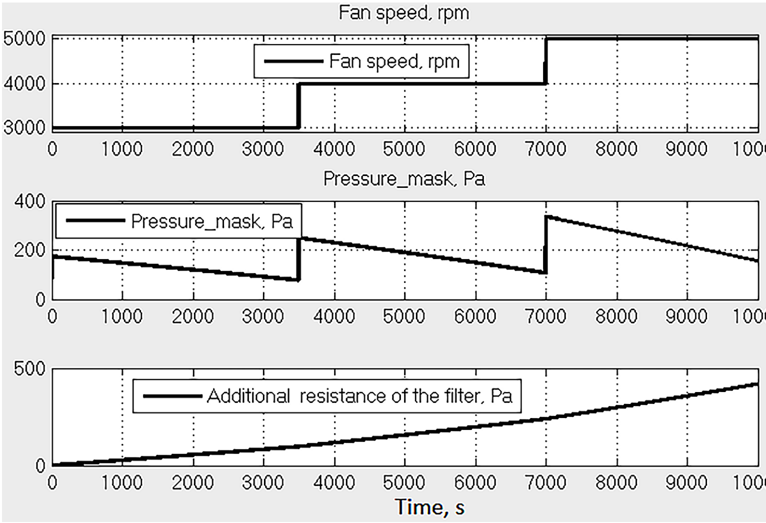


Figure 8. The result of the simulation model operation when the flow rate changes as a controlling action in different operating modes

Source: developed by the authors

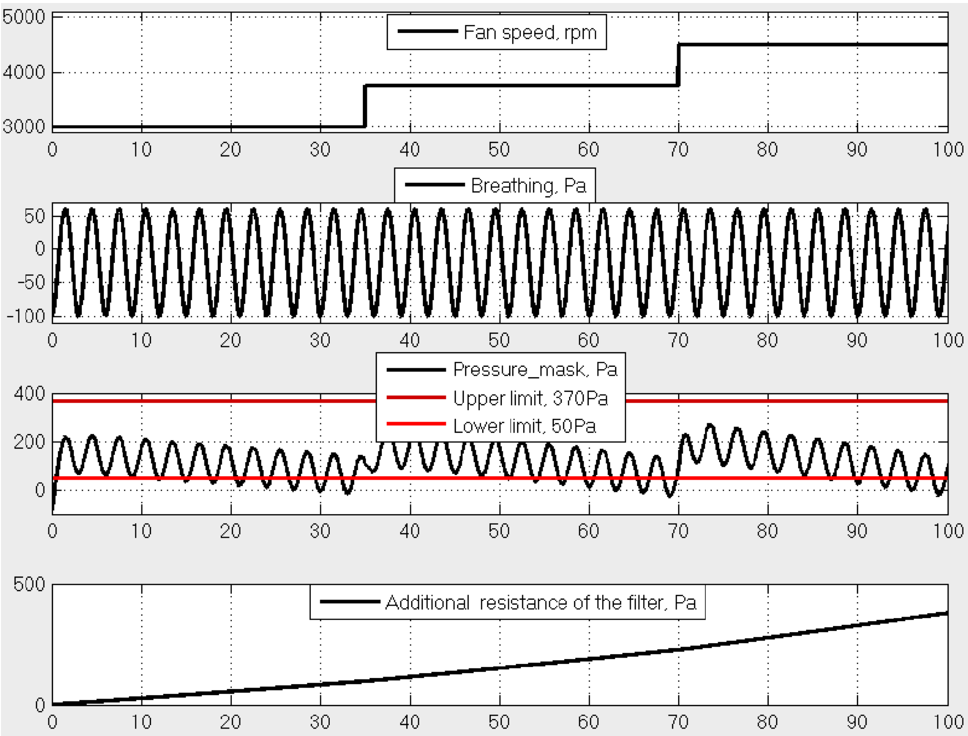


Figure 9. The result of the simulation model operation when adding a breathing signal

Source: developed by the authors

As can be seen from Figure 9, the drawback of the powered air-purifying respirator operation is a drop in the air pressure in the mask beyond the lower permissible limit (below 50 Pa), caused by a change in the pressure drop across the filters due to the lack of a sufficient and timely compensation signal to increase the air supply. This requires an appropriate research on the effect of the change in the additional resistance of the filter due to the dust accumulation on the process of supplying air to the mask, which will ensure the necessary mode of PAPR operation.

When operating the PAPR, an important characteristic is the time of continuous operation from an autonomous power source – the battery. To determine the time of continuous PAPR operation from an autonomous power source, a research was previously conducted to determine the dependence of the consumed electric power of the electronic and electromechanical elements of the control system of the powered air-purifying respirator on the fan speed (Fig. 10).

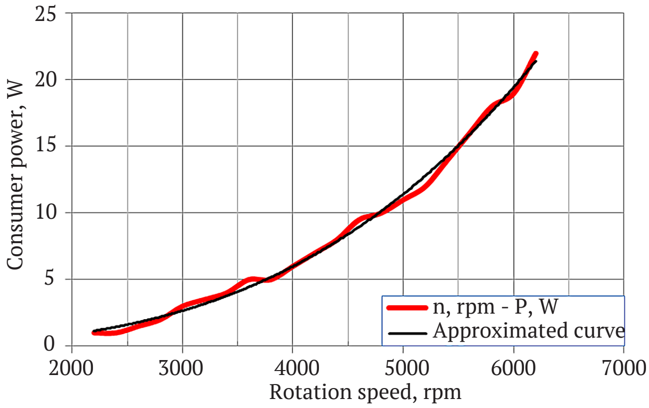


Figure 10. Dependence of power consumption on fan speed

Source: developed by the authors

The equation of the approximate dependence of the consumed power on the fan speed is:

$$y = 8.72E-11x^3 + 1.50E-09x^2 + 9.65E-05x. \qquad (6)$$

Equation (6) being used for the simulation model presented in Figure 9, the possibility of calculating electricity consumption during the operation of a powered air-purifying respirator in the mode of step change of the control signal – fan speed (2-5 levels) was added. The following assumptions were made to conduct the experiment: the levels of the speed change are switched evenly on the time scale and in magnitude, the reverse switching of the levels is not allowed. The simulation results are presented n Figure 11.

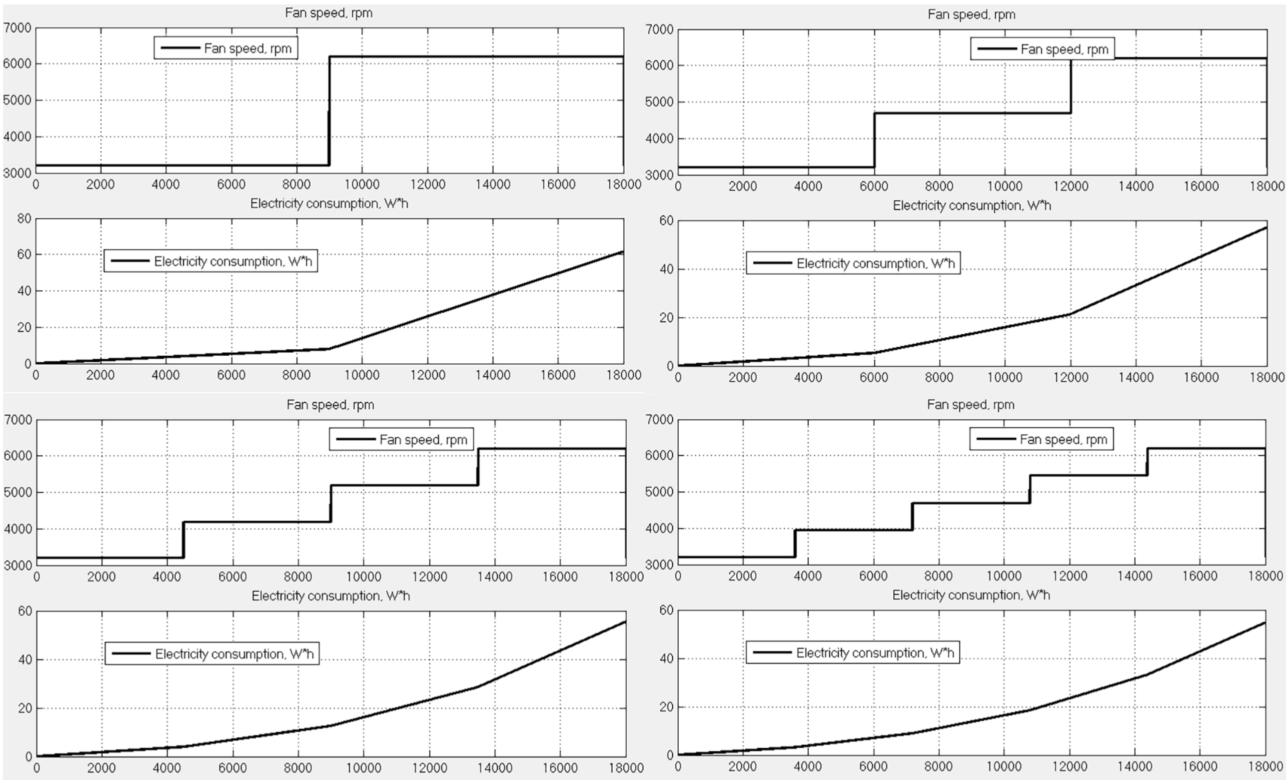


Figure 11. Simulation modelling of electricity consumption during of a powered air-purifying respirator operation in the mode of a step change in the fan speed

Source: developed by the authors

The results of simulation of electricity consumption on a simulated model of a powered air-purifying respirator made it possible to obtain the dependence of electricity consumption on the number of adjustment levels, Figure 12.

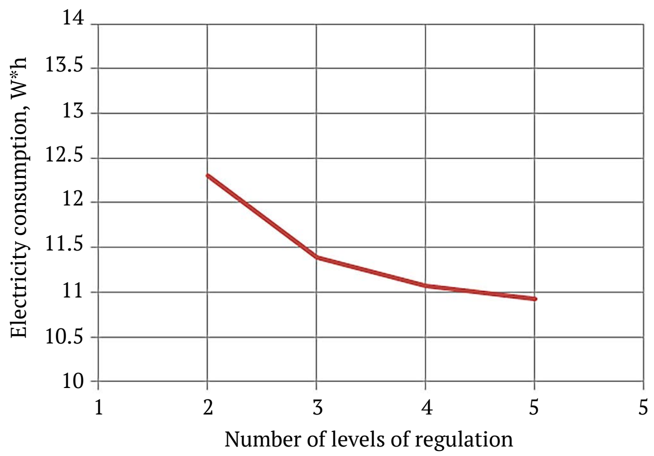


Figure 12. Dependence of average electricity consumption on the number of adjustment levels
Source: developed by the authors

Thus, when increasing the fan speed adjustment levels, for series compensation of the increase in additional resistance on the filter surface, the power consumption is reduced, which allows the use of a battery with a smaller capacity. To ensure continuous operation of the powered air-purifying respirator in autonomous mode at 2 levels of fan speed for 5 hours, the required battery capacity with a voltage of 7.4 V will be:

$$C = \frac{61.54}{7.4} = 8.32 \text{ Ah or } 8320 \text{ mAh}.$$

In view of the standard nomenclature range of storage batteries and taking into account the required reserve capacity at the level of 20%, a battery with a voltage of 7.4 V and a capacity of 10000 mAh can be accepted for use. The obtained curves for the power source as a whole were used when setting the PAPR alarm when the permissible limit level of battery discharge is reached.

As a result of the work performed, the relationship between the change in the breathing resistance of the filters and the discharge of the power source was established, which allows estimating the period of safe operation of the powered air-purifying respirator, based on the concentration of dust in the air of the working area and the user's working arrangements.

Similar results were obtained in the work by S. Wood (2020); however, when developing a simulation model, the author described the operation of the respirator through an analytical method, using the appropriate equations and formulas for individual components. At the same time, the resulting model had several important assumptions and simplifications: the change in filter resistance due to dust accumulation during respirator operation was not considered.

The research by B. Shi *et al*. (2019) analysed the geometric characteristics of the filter, which can increase the efficiency of dust particle capture. The effect of variable air flow on the filter's ability to retain dust over a long period of use is also considered. The emphasis is placed on the relationship between the area of the filter surface and its ability to accumulate dust without reducing efficiency. In addition, the work simulates the behaviour of the filter under the influence of different levels of contamination in order to optimize its operation in real operating conditions.

The work by N. Wagner (2012) was aimed at developing a mathematical model for regulating air supply to the undermask space of a respirator based on the control of a centrifugal fan in automatic mode. The authors reached a number of important conclusions, which were later used when developing a simulation model. In particular, the authors established a relationship between the fan speed and the air flow to the mask, but did not take into account the change in the transmission coefficient in the system when the rotation speed changes in the case when the user needs more air. However, only the case of increased air flow fluctuations in the system was considered when simulating an increase in the depth (amplitude) of the user's breathing, and it was noted that the control system creates prerequisites for delaying the air flow due to a sharp change in the breathing mode when the physical load increases.

The current studies have shown that when using the PAPR, there is a gradual increase in the resistance of the filter elements due to the accumulation of a dust layer, which affects the speed of rotation of the fan blades. As a result, there was a need to develop a simulated model of a powered air-purifying respirator, based on which there are empirical dependencies between the change in filter resistance, the amount of air, and the concentration of dust in the working area air. This made it possible to estimate the additional resistance of the filter due to the accumulation of a dust sediment layer. At the same time, it was assumed that the dust aerosol mostly accumulated on the surface of the filter and did not penetrate deep, creating an additional auto-filtering layer of dust.

CONCLUSIONS

A simulated model of the powered air-purifying respirator has been developed based on its physical model, with allowance for the empirical dependence of the change in the resistance of the filter elements during the accumulation of dust sediment, which takes into account the flow of the air through the filter and concentration of dust aerosol in the air of the working area. The following parameters of the simulated model of the powered air-purifying respirator are substantiated: controlling action – fan rotating speed, restrictions on air flow and air pressure in the respirator mask (it depends on the working arrangements of the user), concentration of dust in the working area air, capacity of the power source, power consumption of the electric motor of the fan and components of the control system, filter element parameters (fibre packing density, filter layer thickness, fibre diameter, etc.), input dust aerosol concentration, which made it possible to establish the relationship between the filter element resistance and the time to complete discharge of the power source.

Simulation modelling of electricity consumption during the operation of a powered air-purifying respirator in the mode of a stepped variation in the fan rotating speed made it possible to establish the dependence of the average electricity consumption on the number of adjustment levels, taking into account two filter elements, and to obtain the equation of the approximate dependence of the consumed power on the fan rotation speed.

A critical value of the resistance of the powered air-purifying respirator filter elements was established, which leads to a significant discharge of the power source, based on the different flow rate of air supplied to the undermask space at a given concentration of dust in the working area. The dependence was determined of the electrical power consumed by the powered air-purifying respirator on the fan rotating speed, which was introduced to the simulation model. According to the simulation results, it was established that with increasing levels of fan rotating speed, the average electrical power consumed decreases, which affects the required battery capacity.

To ensure the continuous operation of a powered air-purifying respirator in autonomous mode with two filters with a total filtering area of 0.01 m^2 and a resistance of 500 Pa at an air flow rate of 140 dm^3/min, with a dust concentration of 0.002 kg/m^3 at 2 levels of fan rotating speed for 5 hours, battery capacity with a voltage of 7.4 V 8320 mAh is required.

Further on, with the implementation of the air pressure control system in the mask of the powered air-purifying respirator, the average power consumption may decrease, consequently, reducing the battery capacity requirements. Considering the fact that the battery capacity determines its weight and cost, this will also reduce the finished cost of the device. The introduction of a powered air-purifying respirator, as the main means of individual respiratory protection at mining enterprises, should, in the long term, improve the health of workers who perform their professional duties in conditions of excessive dust concentration in the working area air.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Дослідження впливу опору фільтруючих елементів на термін експлуатації моторованих респіраторів

Анотація. Метою дослідження було визначення впливу зростання опору фільтруючих елементів на термін експлуатації моторованих фільтрувальних респіраторів під час експлуатації в гірничих умовах та обґрунтування параметрів джерела живлення респіратора Дослідження проводилося методом комп'ютерного імітаційного моделювання роботи моторованого респіратора, що дозволяє обчислити додатковий опір фільтра через накопичення пилу. Імітаційна модель моторованого респіратора була створена на основі його фізичної моделі та, з урахуванням емпіричної залежності зміни опору фільтрувальних елементів при осіданні пилу, дозволяє визначити витрату повітря через фільтр та концентрацію пилового аерозолю в повітрі робочої зони. Обґрунтовані параметри імітаційної моделі моторизованого респіратора: керуючий вплив – швидкість обертання вентилятора, обмеження по витраті повітря та тиску повітря в масці респіратора (залежить від режиму фізичної роботи користувача), концентрація пилу в повітрі робочої зони, ємність джерела живлення, споживану потужність електродвигуна вентилятора та компонентів системи керування, параметри фільтрувальних елементів (щільність пакування волокон, товщину фільтруючого шару, діаметр волокон та інше), вхідну концентрацію пилового аерозолю, що дозволило встановити залежність між величиною опору фільтрувальних елементів та часом до повної розрядки джерела живлення. Встановлено критичну величину опору фільтрувальних елементів моторованого респіратора, яка призводить до значного розряду джерела живлення, виходячи з різної витрати повітря, що подається у підмасковий простір при зданій концентрації пилу в робочої зоні. Встановлено залежності між зміною опору дихання фільтрів і розрядом джерела живлення, що дозволяє встановити термін безпечної експлуатації моторованого респіратора, виходячи із концентрації пилу в повітрі робочої зони та режиму роботи користувача. Практичне значення полягає у визначені терміну експлуатації моторованого респіратора, виходячи з критичної величини опору фільтра, який призводить до швидкого розрядження джерела живлення

Ключові слова: керуючий вплив; імітаційна модель; об’єкт керування; ідентифікація; дослідження; витрата повітря; акумулятор; електроенергія; тривалість роботи

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Examination of maintainability indicators of feed preparation and distribution products

Abstract. New scientific and practical approaches in the livestock industry use Industry 4.0 and IoT technologies, in particular, feed mixers, for efficient transportation and dosing of feed, but the reliability problems of these mechanisms require research to determine the parts and assemblies that limit their performance and calculate their maintainability. The purpose of this study was to establish the design, production, and operation failures of feed mixer mechanisms, the causes of their occurrence, and the time to eliminate them. For this purpose, an examination of feed mixers was conducted according to the reliability test plan [NMT]. The test plan provided for the presence of *N* objects, which were restored in case of working capacity loss by *M*, and experiments are stopped when the operating time *T* was reached. The initial information was collected and processed, and empirical data were analysed to eliminate failures of the PROFILE 12.2 DS and PROFILE 14.2 DS feed dispensers. The tests established that during the warranty period of operation of feed dispensers, their faulty condition is caused by failures of the second group of complexity. Failures related to the restoration of the working capacity of the subsystem for grinding and mixing, which affects the maintainability of the feed dispenser mixer, are identified. A

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statistical analysis of the occurrence of these failures was conducted. The main parameters of the theoretical distribution law were determined. In particular, the maintainability indicators of feed dispensers were established: the average recovery time of working capacity, $\bar{t}$ = 24.0 hours; mean square deviation, σ = 12.93 hours; coefficient of variation, υ = 0.49; the theoretical distribution law – the law of normal distribution. It was confirmed that the average recovery time of feed dispensers according to the Kolmogorov consent criterion was in good agreement with the law of normal distribution. Calculations established that the average time for restoring the operability of research objects was in confidence intervals: 6.98 hours – lower confidence limit; 41.02 hours – upper confidence limit; 34.04 hours – the size of the interval. The results can be implemented to improve the efficiency of maintenance and repair of equipment on livestock farms and optimise spare parts stocks

Keywords: feed dispenser mixer, operational reliability, time to failure, recovery time, grinding-mixing mechanism

INTRODUCTION

The study on maintainability indicators is necessary to ensure continuous operation of the enterprise, reduce maintenance costs, minimise downtime, increase the efficiency of production processes, extend the service life of equipment, optimise spare parts stocks, improve the design of new models, develop recommendations for operation and improve labour safety. This allows timely detection and elimination of potential failures, preventing their transformation into serious breakdowns, and contributes to more accurate planning of repair and preventive measures, ensuring stable and efficient operation of livestock farms.

The relevance of research in the field of precision animal husbandry, which has spread to Europe, Asia, and America since its formation in 2003, is noted. New technological approaches in the livestock industry take advantage of advances in Industry 4.0 and IoT technologies, covering economic, technological, logistical, and social aspects (Norton *et al.*, 2019). Authors U. Moallem & L. Lifshitz (2020) note that for the sustainable and effective development of animal husbandry, it is advisable to use modern feeding technologies, justify highly efficient and improve the available means for loading, grinding, mixing, transporting, distributing, and dosing feed mixtures. The quality level and volume of livestock products largely depend on the duration of the feeding process.

The diversity of cattle species and their age groups, the difference in their conditions of keeping and differences in livestock, require designers and machine builders of agricultural machinery to produce efficient, high-performance, and reliable machines (Novitsky *et al.,* 2023). Along with substantiating the main parameters of the horizontal coarse feed grinding mechanism, K. Astanakulov *et al*. (2020) manufactured and conducted experimental studies on a small-sized feed dispenser with a vertical screw, including testing the performance of the technological process and determining optimal parameters. P. Ma *et al*. (2020) conducted an examination of the design and technological characteristics of the grinding mechanism – a mixer with a horizontal screw. The main tests in this paper were: multiplicity of technological operation; number of fixed blades; grinding speed; number of working bodies; angle of inclination of the mixer body components.

Among the main scientific and practical searches that form a highly productive provision of feed preparation, the following should be mentioned: computerisation of the technological process; technical service of machines and equipment; ensuring maintainability; training and advanced training of personnel.

Agricultural engineering plants produce trailed and self-propelled mixers-feed dispensers, which, depending on the design, can provide a set of measures for feed preparation and distribution of mixtures. Researchers S. Morrone *et al*. (2022) state that at all stages of mixers-feed dispensers use, according to their functional purpose, attention should be focused on ensuring zootechnical requirements, reducing the consumption of feed components, improving the nutritional value of feed mixtures, improving their quality indicators.

During the operation of mixers, it is necessary to ensure a high level of maintainability indicators. Failure of any mechanism leads to a disruption of the entire complex of technological operations that feed mixers provide according to their structure and purpose. This can lead to a decrease in the level of operability of funds both during running-in, warranty service, and during the period of operation.

As noted by F. Tian *et al.* (2020), it is especially important in the operation of complex agricultural machinery to ensure and maintain the reliability parameters that were laid down at the stages of design, construction, production, and commissioning. The most important period is the initial period of use of agricultural machinery – the period of running-in. Violation of the rules of operation and maintenance of machines during the warranty period can reduce the reliability of the machine and lead to malfunctions and failures. It is necessary to perform maintenance and repair work to prevent failures and ensure the operability of machinery and equipment for animal husbandry. Based on the above, conducting research on calculating and ensuring the maintainability of feed dispensers is an important and urgent task.

The purpose of this study was to determine the design, production, and operational failures of feed mixer mechanisms, the causes of their occurrence, and the time to eliminate them.

LITERATURE REVIEW

The organisation of the technological process of feed preparation is a promising direction for reducing costs in the livestock industry, as noted by V. Khmelovskyi *et* *al.* (2020). The search for ways to reduce the energy intensity of this process is inextricably linked with the technology of preparing feed for feeding, the size of the livestock farm, and the choice of technological means for preparation and distribution.

Authors D. Wang *et al*. (2017) justified the parameters of the screw with the angle of installation of turns, improved the design of the hopper body, and determined their impact on the quality preparation of the feed mixture. They recommend ensuring the speed of rotation of the screw of the grinding and mixing subsystem close to 32.5 minutes^{-1}. The preparation time of a high-quality feed mixture is 4.7 minutes. However, it is important for operators to be able to assess the impact of these changes in the design of the auger, hopper, and operating modes of the grinding-mixing mechanism on the efficiency of use and reliability indicators of feed preparation and distribution products. Consumers are interested in the probability of parametric failures when using feed dispensers when grinding various feeds.

V. Baranovsky *et al.* (2018) proposed materials of analytical justifications for the transportation of agricultural products in fixed screw conveyor housings. These results of investigations of materials transportation operations by screw conveyors confirmed the possibility of their use in the design of mechanisms for loading and unloading agricultural machines, increasing their reliability indicators. Due to the increase in the volume of foreign means for feeding on livestock farms in Ukraine, it is timely to assess their maintainability since machine-building enterprises do not provide consumers with values of reliability indicators of the presented machines. This problem is reflected in separate papers by F. Tian *et al.* (2020), but these studies do not provide quantitative and qualitative indicators of maintainability and a set of measures to improve them for profile feed dispensers in Ukraine.

S. Morrone *et al.* (2022) note that animal husbandry can be highly efficient only due to a high-quality technological process of feeding, the use of computerisation, and the efficient technical service of feed preparation machines on demand. Therewith, as the analysis of the reliability of these tools shows, the complexity of their design, the tension and the short duration of their use in animal feeding technologies require the implementation of effective measures to ensure maintainability indicators.

As noted by M. Dumenko *et al.* (2012), maintainability indicators provide for determining the average time spent on ensuring operability, evaluating the values of criteria for the maximum condition of blades, rational methods for restoring parts, methods for ensuring the effectiveness of maintenance and repair in the conditions of the existing repair base or at different levels of the potential of the maintenance base.

According to D. Domushchi *et al*. (2019), recorded downtime of multi-operating machines, in particular, combine harvesters, reaches from 25 to 75% of the total time of their use during the day. The reason for substantial time spent on restoring the working capacity of research objects, as a rule, can be: a lack of spare parts; insufficiently developed structure of technical service, and insufficient qualification of personnel who provide technical supervision and repair of equipment. For prompt access to spare parts that are necessary to ensure the operability of combine harvesters, the authors of the article propose to introduce the following system of storage of parts: spare parts necessary to eliminate failures of the first group of complexity, are to be stored on the combine itself or at a mobile maintenance point; eliminate failures of the second group of complexity – in the warehouse of an agricultural enterprise or in the warehouse of a department; for the third group of complexity – in the warehouse of a regional service centre.

In connection with the above, there is a need to form a list of parts and components that often lose their functionality, and the quantity that must be reserved at different storage levels: directly on the mixer-feed dispenser; in the warehouse of an agricultural firm; in the dealer's mobile maintenance point; in the warehouse of the dealer's service centre. It is also necessary to determine the list of works that operators need to perform during the function of feed dispensers. Solving these tasks will help to reduce the time spent for organisational reasons when eliminating the consequences of failures, achieve the highest operational efficiency, and ensure the productivity of funds at the lowest cost of material and labour resources under various conditions for performing feeding operations.

In separate scientific publications and conference materials, the issues of justifying the optimal idle time of feed mixers due to the elimination of the consequences of failures are considered. In particular, Z. Ruzhylo *et al.* (2022) review the load on one vehicle and substantial production factors that affect the reliability of equipment and the timeliness of their elimination. It is important to consider individual components of a complex technical system, record the time of time between failures of the "machine" and the time of performing functions by the "human operator", and calculate the intensity of transitions. Substantial production factors include timely restoration and maintenance of the working capacity of the "human operator" through the use of "failure harbingers" and improving their skills.

In general, the examination of the causes and consequences of equipment failures for animal husbandry is conducted to make informed and effective decisions regarding the mode of operation and maintenance of machines. Thereby, it reduces the probability of failures and the complexity of eliminating their consequences, which may lead to the disruption of zootechnical requirements, postponement or non-fulfilment of the technological process of feed preparation and distribution. Based on the results of the analysis of special literature and guidelines for use, it was determined that long-term downtime of feed dispensers is associated with untimely recovery of working capacity.

MATERIALS AND METHODS

The study was conducted at the National University of Life and Environmental Sciences of Ukraine. The results of analytical searches and tests presented in the study are a continuation of findings by A. Novitsky *et al.* (2023), Z. Ruzhylo *et al.* (2022). They are aimed at ensuring the reliability of mixer dispensers during operation and during the restoration of operability through maintenance and repair. The objects were mixers-feed dispensers PROFILE 12.2 DS and PROFILE 14.2 DS (Novitsky *et al.,* 2023) (Fig. 1a). The diagram of the research object is shown in Figure 1b.

a) b)

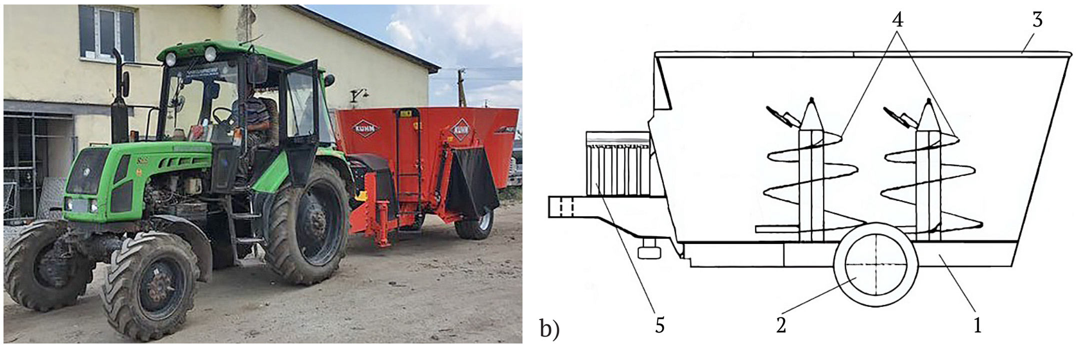

Figure 1. Feed dispenser mixer PROFILE 14.2 DS

Note: a – under operating conditions; b – diagram of the mixer-feed dispenser; 1 – frame; 2 - Running system; 3 – hopper; 4 – grinding-mixing mechanism; 5 – mechanism for unloading the feed mixture

Source: compiled by the authors

Time-based observations were made on the use, maintenance, and repair of means for preparing and distributing feed in the period from 2015 to 2022 to collect statistical information on maintainability indicators in agricultural enterprises. The study involved 25 feed dispenser mixers "PROFILE 12.2-14.2" (Operator's manual..., 2018; Operator's manual. Mixer feeder wagon. PROFILE. 2DS, 2019). The tests were conducted on livestock farms in seven regions of Ukraine. In each of the presented regions, the following number of mixer distributors was tested: Khmelnytskyi – 9; Vinnytsia – 6; Zhytomyr – 3; Cherkasy – 3; Chernihiv – 2; Volyn – 1; Poltava – 1.

Timekeeping data was entered in the summary form. Failures were classified into difficulty groups. Failures that could be eliminated by adjusting, replacing, or repairing parts included in the spare parts kit, without disassembling components and assemblies, were divided into the first group. Malfunctions and defects that were eliminated by adjusting, rearranging, or repairing parts that are not included in the spare parts kit, with the disassembly of components and assemblies, as well as with the use of mobile maintenance points or mobile repair shops, were included in the second group of complexity. Failures that require dismantling components and assemblies from the frame of the feed dispenser mixer or completely replacing one of them were assigned to the third group of complexity. Failure of the working body or parts of the mixer-dispenser that caused complete or partial loss of performance of other parts were registered as one. Thus, the complexity group was determined by the greatest complexity of restoring one of the failed parts.

During the testing of feed dispensers, failures were recorded, and maintainability indicators were established. Failures of the presented research objects were distributed across the subsystems shown in Figure 1b.

The mixer dispenser is equipped with A5336551 screws (KUHN, France). Each of the screws of the grinding-mixing mechanism is equipped with the appropriate number of blades (Audureau S.A. plant, KUHN Group, France), according to the design of the profile mixer-dispenser. Blades on the auger are installed in two versions according to the manufacturer's recommendations: the small blade A5362450 has 7 teeth and is fixed on the lower ones, and the large knife A5303620 includes 9 teeth and is placed on the upper turns of the auger of the subsystem for grinding and mixing feed mixture.

The test mode of means for the preparation and distribution of feed is established as operational at the place of production. The plan for testing feed mixers for maintainability [NMT] has been adopted. The [NMT] plan considers the availability of an appropriate number of test objects N, which are restored in case of working capacity loss are restored by M. The test plan stipulates that experiments are suspended when the appropriate time T is reached, which is spent on restoring performance. Based on the above, for the described test plan [NMT], the initial parameters are as follows: the number of feed mixers N, pieces; the property of the presented means to be restored in the corresponding average time T, hours. The initial data were set, which indicated the accuracy of the obtained results to establish the minimum volume of observations It included confidence probability and marginal relative error, which were $\gamma = 0.9$ and $\delta = 0.1$, respectively. According to a priori data, it was determined that the distribution of values for restoring the operability of feed mixers corresponds to the law of normal distribution.

Using reference information (DSTU 3004-95, 1995), the minimum number of objects under the presented tests was calculated $N_{min} = 21$, $N = 25$ feed dispensers were taken. The distribution of the average recovery time of working capacity is in good agreement with the law of normal distribution, according to $\gamma = 0.9$ and $\delta = 0.1$.

Statistical processing of experimental data was conducted as follows: according to the obtained empirical data, a statistical series of information was formed; an empirical distribution was constructed; distribution parameters were calculated; a hypothesis was formed about the type of distribution law of the random variable that was examined; according to the accepted theoretical law, the empirical curve was aligned; according to the consent criteria, an empirical and theoretical distribution was compared; in accordance with the results, a decision was made to accept or deny the proposed hypothesis.

The method of processing experimental data provides for the calculation of the following maintainability indicators: average recovery time of working capacity; mean square deviation of the indicator; coefficient of variation; theoretical distribution law; scattering intervals of empirical values of the average recovery time of working capacity.

RESULTS AND DISCUSSION

The strategy for the development of the agro-industrial complex of Ukraine encourages the purchase of a substantial amount of new national and foreign equipment, including feed mixers. The design schemes of feed dispensers are diverse. According to the method of aggregation, they are divided into self-propelled and trailed. Trailed ones were more popular in small farms (Ruzhylo *et al.,* 2022), and at large livestock enterprises – self-propelled (Tian *et al.,* 2020). Most of them consist of a single-axis or two-axis chassis, on which a hopper with mixing working bodies, a transverse unloading conveyor, and an unloading system are fixed. The working bodies of these machines are driven from the tractor's PTO shaft. The mixing working bodies of the presented tools are augers with blades, which are located inside the hopper and are installed in accordance with the horizontal and vertical schemes. The number of mixing working bodies can vary from one to four.

The obtained time values for transferring PROFILR trailed vehicles to working or serviceable condition are taken from the timekeeping data of the official dealer – KUHN in Ukraine. According to the results of the conducted studies, the time for restoring the operability of 25 feed dispensers was recorded, which is shown in Figure 2.

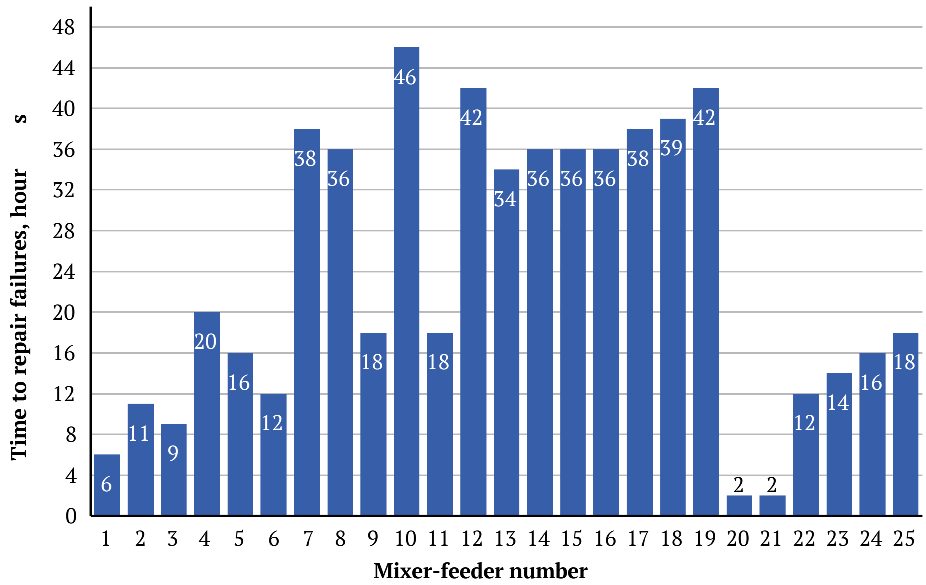

Figure 3. Recovery time for feed preparation and distribution tools PROFILE 12.2 DS and PROFILE 14.2 DS
Source: compiled by the authors

An analysis of the results shows that the minimum recovery time was 2 hours for research objects No. 20 and No. 21. The maximum recovery time is 46 hours for object No. 10 and 42 hours for objects No. 12 and 19. Failures that limit the reliability of feed dispensers were identified. It was determined that 92% of failures of objects under study recorded during observations belonged to the second group of complexity. They were eliminated by replacing easily accessible parts and components, which required the disassembly of units or extraordinary maintenance operations. An analysis of the maintainability indicators of mixers-distributors showed that the most characteristic failures that led to the loss of performance were failures of the working bodies of the grinding-mixing mechanism and the hopper.

During the tests, statistical data on the time of restoration of serviceability or operability of feed dispensers were obtained, which reflect the values of maintainability indicators. A table of statistical information was formed (Table 1) to process the obtained data and calculate the value of the indicator of the recovery time of the presented tool.

Table 1. Statistical time series for eliminating failures of feed dispensers

No.	Borders intervals	Mid-interval	Frequency, m_i	Experimental probability, *Pi*	Accumulated experimental probability, ΣP_i
1	2.0-10.8	6.4	4	0.16	0.16
2	10.8-19.6	15.2	9	0.36	0.52
3	19.6-28.4	24.0	1	0.04	0.56
4	28.4-27.2	32.8	5	0.2	0.74
5	37.2-46.0	41.6	6	0.24	1.0

Source: compiled by the authors

After grouping the values of the recovery time indicators by intervals, the failure rate, experimental probability, and accumulated experimental probability were determined. The obtained values of the empirical distribution of time for restoring the operability of feed preparation and distribution facilities are given as a statistical series of information (Table 1) and graphically (Fig. 3). Histogram analysis (Fig. 3) allows noting that the graph is characterised by five specific time periods in accordance with the failures that were eliminated. The lowest probabilities of events, 0.16 and 0.04, are characteristic of the first and third intervals, which correspond to the failure elimination time intervals of 2.0-10.8 hours and 19.6-28.4 hours. The second and fifth intervals, which correspond to the failure elimination time intervals, are characterised by the highest probability, 0.36 and 0.24 10.8-19.6 hours and 37.2-46.0 hours. Time to eliminate failures, fixed within the limits of 10,8-19,6 hours, corresponds to the work that consists in replacing the auger with blades or blades of the subsystem of grinding and mixing feed dispensers, the service life of which has reached more than 3 years. Time to eliminate failures within the limits of 37.2-46.0 hours was recorded for feed dispensers for which the warranty period of 1 year has expired.

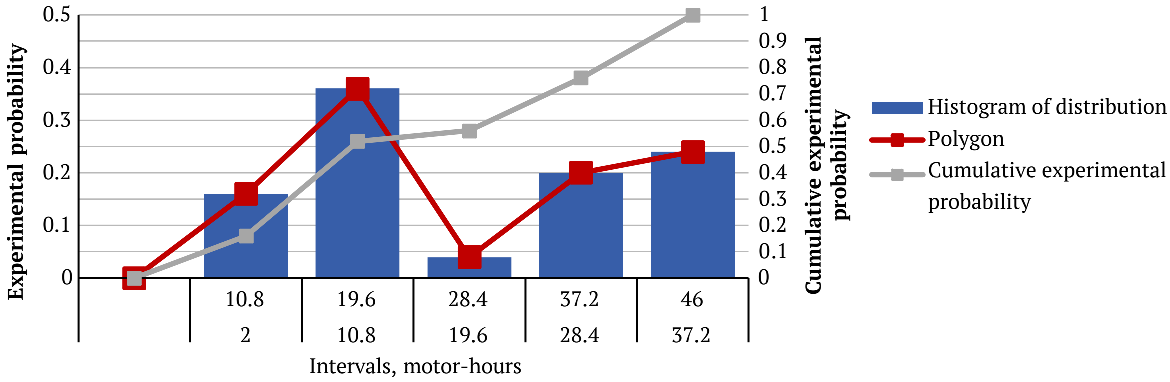

Figure 3. Graphical representation of empirical distributions of the maintainability indicator of feed dispensers under operating conditions

Source: compiled by the authors

After processing the values of the time to restore the operability of feed mixers, it was established that the resulting array of empirical data is characterised by the following indicators:

- average recovery time, $\bar{t}$ =24.0 hours;
- mean square deviation of the recovery time, σ = 12.93 hours;
- coefficient of variation of a random value, υ = 0,49.

It is assumed that the time that must be spent on eliminating failures of feed dispensers according to DSTU 3004-95 (1995) is consistent with the theoretical law of normal distribution. Verification of the correspondence of the time values for restoring working capacity within the theoretical distribution law and the empirical distribution for the mechanism of grinding and mixing research objects was performed according to the consent criterion λ of O.M. Kolmogorov.

Since the resulting value $P(\lambda)$ = 0.9972 is more than the accepted level of significance for the normal distribution law, then the considered condition on the compliance of theoretical and experimental data with the time of recovery of the working capacity of the Weibull-Gnedenko law is rejected (DSTU 3004-95, 1995). The limits of confidence intervals and the value of the scattering interval of the average value of elimination of failures of feed distribution mixers according to the adopted theoretical distribution law are calculated according to the corresponding analytical dependencies (DSTU 3004-95, 1995). The results of these values, respectively, amounted to:

$t^{н}_{90} = 6.98$ hours – lower confidence limit;
$t^{в}_{90} = 41.02$ hours – upper confidence limit;
$I_{90} = 34.04$ hours – the size of the interval.

Previous studies by A. Novitsky *et al.* (2023) established that the reliability of the feed mixer is limited by the grinding and mixing subsystem. The maintainability of the machines forms an indicator of the time to restore their operability, including the replacement of blades, sets of screws with blades, and restoration of the hopper body.

According to the guidelines for use, the PROFILE feed dispenser mixer, which is presented in the studies, contains two vertical augers in its design. The number of blades attached to one screw, respectively, is 6 small, and 2 large. It is this complete set of blades that must be available among spare parts at the appropriate storage levels to ensure the maintainability of the feed dispenser mixer: level I – directly on a livestock farm or warehouse of an agricultural firm; Level II – mobile service point of the KUHN group of companies; level III – warehouse of the KUHN group of companies.

Figure 4 shows the time to failure and time to eliminate failures of 25 profile feed preparation and distribution products. For most feed dispensers, a correspondence is recorded between the maximum time to failure and the maximum time to restore operability. For mixers-distributors No. 6-14 within the time limit for failure of 3000-5000 hours, an increase in the time to restore working capacity was recorded within the maximum values – from 38 to 46 hours. For objects No. 15-19 which have a failure time of 500-1500 hours, there was a slight increase in the time to restore workability, which is 38-42 hours. The specified time is required to restore the working capacity of the hopper or screws with the replacement of blades.

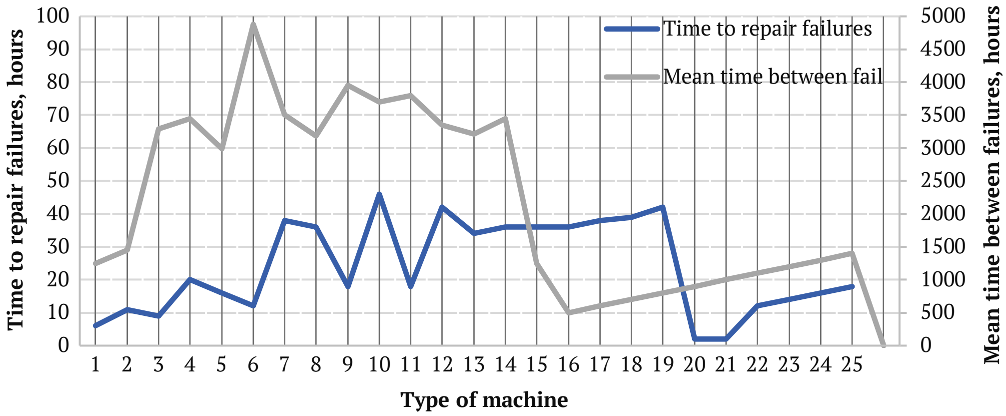

Figure 4. Value of time to failure and time to eliminate failures of feed dispensers
Source: compiled by the authors

From the analysis of the above results of the time to failure examination and the values of the time to restore the operability of mixers-feed dispensers and to increase their reliability during operation, it is necessary to include in the list of maintenance works of the grinding-mixing subsystem information about the list of parts and working bodies that must be at different storage levels. Such an addition will allow increasing the value of the readiness coefficient of the product for preparing and distributing feed, reducing downtime and time spent on restoring working capacity.

For the highly efficient use of feed mixers, it is advisable to analyse the actual level of reliability indicators, including reliability, durability, maintainability, and safety (DSTU 3004-95, 1995). Such experimental studies allow identifying general dependences of changes in reliability indicators in different periods of the service life of objects under study. This is especially important during the warranty period for identifying structural and technological defects and malfunctions of feed dispensers, justifying recommendations for improving their maintainability.

Based on this, a thorough assessment of reliability is necessary to identify system bottlenecks and search for subsystems or components with a low maintainability value. The implementation of a given project productivity and efficiency can be evaluated on the example of complex technical systems that are used in industrial engineering facilities. Of particular interest is not only the readiness of complex technical systems – agricultural machinery and equipment – to work at any given time or their reliability over a certain period but also an indicator of how quickly this system can return to operation after each failure. These issues were thoroughly analysed in the papers of a number of researchers who not only received the value of time to failure in operating conditions, set the time to restore performance but also investigated the issues of ensuring the reliability of mechanisms of various machines, in particular:

- threshers (Sharma *et al.*, 2022);
- motor cultivators (Katsitadze *et al.* 2021),
- combines (Najafi *et al.*, 2015);
- machine-tractor units (Rogovskii *et al.*, 2021);
- transport and technological machinery (Aulin *et al.*, 2024).

The scientific-methodological approaches proposed in these studies have every reason to be used to determine the maintainability of feed dispensers and evaluate and ensure their reliability indicators.

In the study by J. Katsitadse *et al.* (2021), the results of evaluating the operational reliability of tillers, which represent a substantial group of machines and equipment used in agricultural production, are reflected. The presented methodology for calculating reliability indicators confirms the importance of forming a method for ensuring the reliability of machines, including maintainability.

From the experience of using and examining the results of experimental data on the reliability of feed mixers during operation and literature sources, it can be concluded that most researchers conducted a scientific search to determine and form the structural, technological, functional, and operational parameters of self-propelled and trailed vehicles for the preparation and distribution of feed. The materials reflected in the publications of recent years are important when discussing the results of the presented findings on self-propelled and trailed mixers for feed preparation.

F. Tian *et al*. (2020) offer a number of theoretical recommendations for improving the structure, technical, and functional characteristics of self-propelled equipment for mixing and distributing feed mixtures. Based on the results of experiments, the authors propose to optimise the operation of the loading mechanism and the grinding-mixing mechanism by combining shear, diffusion, and convective motion in the equipment hopper.

S. Şeflek & H. Haciseferoğullari (2018) investigated the maintainability of the planetary transmission mechanism of the vertical screw drive of the feed mixer R6 and indicated characteristic damage to parts. According to the test results, most of the failures were caused by cracks, fractures, and corrosion on the gears and auger. St37 steel was chosen to increase the service life of the vertical auger. However, the materials presented in the study do not contain values of reliability indicators for serial and experimental working bodies and parts of the feed mixer. There is not enough information about the level of maintainability of the feed mixer. Therewith, the practice of using the equipment of the PROFILE model range showed that two cases were recorded when uneven wear of the turns of the screw and blades led to uneven operation of the drive elements and loss of performance of the grinding-mixing mechanism.

V. Khmelovskyi *et al*. (2020) considered the use of mobile feed preparation equipment with feed mixture feeding to feed tables in livestock farms. considered the use of mobile feed preparation equipment with feed mixture feeding to feed tables in livestock farms. An important design and technological characteristic of the tool is the self-cleaning property of the screw, which ensures safety and maintainability indicators, especially in the autumn-winter period of its use. It is advisable to establish the relationship between the authors' recommendations for improving the structure and quantitative indicators of maintainability and safety in further studies on the reliability of mixer dispensers.

S. Postelga *et al.* (2021) presented the methodology and test results of a self-propelled mixer dispenser from the German company Siloking, SelfLine 4.0 Premium 2215. The materials presented in the study were obtained by the author in the process of performing the technological operation of preparing and distributing the feed mixture by self-propelled transport-technological machines. In the process of testing and testing the mixer-dispenser, the effectiveness of its use for feed preparation of cattle and ensuring the uniformity of feed mixing of 94.3% and the uniformity of distribution – 95.5%, were confirmed. The study does not contain the results of evaluating the reliability indicators of a self-propelled mixer-dispenser, which ensured efficient preparation and distribution of feed mixture according to the materials declared by the author.

O. Dereza *et al*. (2021) analysed the specific features of using vertical and horizontal feed mixers of all types in the agricultural sector of Ukraine and formed the main reasons that limit their widespread introduction into the livestock industry. Among the most substantial problems, as the authors note, are: the lack of a comprehensive approach to the introduction of modern achievements in feeding technologies; justification of the action of a human operator in solving problems of safety of equipment and ensuring operability; the implementation of a complex of works on timely maintenance of feed mixers; reconstruction of farms of old buildings for the implementation of modern technologies for the production of feed mixtures. One of the reasons for the poor quality of maintenance and repair of feed mixers is the lack of information about maintainability indicators and the main components that form this property. These conclusions confirm the importance and relevance of the presented findings.

Several researchers in their studies presented theoretical examinations of the parameters of aggregates of agricultural machinery and equipment. V. Bulgakov *et al.* (2023) presented a methodology for the examination of such an operational indicator of agricultural machine and tractor units as smooth running, which affects the traction and dynamic performance of their work, productivity, agrotechnical quality of operation, durability, and economy. The method of mathematical modelling and experimental determination of vertical vibrations of the unit declared by the authors of the study can be used to examine the dynamics of movement of other agricultural machinery and equipment, including self-propelled and trailed transport-technical machines.

Analysing the results of tests for the maintainability of feed mixers PROFILE 12.2 DS and PROFILE 14.2 DS and studies that implement separate scientific and practical approaches to the formation of reliability of machines and equipment for animal husbandry as complex technical systems "man – machine – environment", special importance in ensuring the operability of machines is assigned to the human factor.

In many papers, along with the design, production, and improvement of individual mechanisms of these tools, the influence of the "human-operator" component on the reliability of the "man – machine – environment" technological system is evaluated. H.-W. Lo *et al.* (2019), R. Amaya-Toral *et al.* (2022) noted that the improvement of reliability and maintainability indicators in the operation of machinery and equipment, reducing the possible risks of failures during the production process largely depends on the influence of the human factor of the "human operator" component. J. Vegricht *et al.* (2007) determined that the energy consumption and capacity of a machine for loading feed from storage depends on the experience and professional qualities of operators, a detailed examination of the technical condition of the working bodies of mechanisms.

The experience of using analytical approaches and methods of expert assessment of personnel can be used in justifying and ensuring the reliability of technological and technical systems. The obtained values and the practice of maintaining the serviceability and operability of machines confirmed the possibility of using analytical approaches and test results to ensure the reliability of not only feed mixers but also machines, stands, and equipment of repair and service enterprises.

During the examination of the processes of maintaining the serviceability and operability of feed dispensers under operating conditions, it was established that one of the causes of malfunctions and failures is the lack of information in the regulatory and technical documentation about maintainability indicators, criteria for the onset of the limit state of the working bodies of the feed grinding and mixing subsystem (Novitsky *et al.,* 2023). O. Dereza *et al*. (2021) note that agricultural enterprises that have purchased European-made feed mixers often encounter cases where there is no timely supply of spare parts and qualified repairs, especially in the post-warranty period. The practice of using feed mixers has revealed that one of the main reasons for the formation of malfunctions and defects is deviations from the frequency of maintenance and assessment of the technical condition of parts. Other characteristic reasons for the appearance of malfunctions and defects are a decrease in the reliability of the "human operator" and low control over the main parameters of the technical condition of the means for feed preparation, mixing, and distribution of feed mixtures as a complex technological system.

The study presents the results of testing and processing information on the maintainability indicators of means for preparing and distributing feed under operating conditions. The presented methodological approaches can be implemented by improving the design, technical and functional parameters, justifying individual and complex reliability indicators of feed distribution mixers.

CONCLUSIONS

Based on the results of the reliability assessments of 25 feed dispensers during operation, information was obtained about the maintainability of PROFILE 12.2 DS and PROFILE 14.2 DS, and the recovery time in case of loss of performance was established. The resulting array of data on the recovery time of feed dispensers is characterised by the following values of indicators: average recovery time of working capacity, $\bar{t}$ = 24.0 hours; mean square deviation, σ = 12.93 hours; coefficient of variation, υ = 0.49; the theoretical distribution law is the law of normal distribution. The consistency between the theoretical law and the empirical distribution of the time of recovery of the tool's operability according to the O.M. Kolmogorov criterion is confirmed. Studies have established that the value of the average recovery time of feed dispensers, according to the normal law, is in confidence intervals: $t_{90}^{\text{н}}$ = 6.98 hours – lower confidence limit; $t_{90}^{\text{в}}$ = 41.02 hours – upper confidence limit; I_{90} = 34.04 hours – the size of the interval.The second and fifth intervals are characterised by the highest probability of events, 0.36 and 0.24, which correspond, respectively, to the failure elimination time intervals 10,8-19,6 hours and 37.2-46.0 hours. Specified failure elimination time was recorded within the limits of 10,8-19,6 hours, corresponding to the work that consists in replacing the auger with blades or blades of the subsystem for grinding and mixing feed dispensers, the service life of which has reached more than 3 years. The time for elimination of failures is set within the limits of 37.2-46.0 hours for feed dispensers with an expired warranty period.

In further research, analytical methods of calculation and directions of the programme for forming the reliability of feed mixers as technical systems "man – machine – environment" will be used, and measures will be developed to reduce the probability of failures depending on: the impact of the "man – operator" component, considering professional level and work experience; on the efficiency of the maintenance and repair system in the conditions of the existing repair and maintenance base or at different levels of the maintenance base potential.

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CONFLICT OF INTEREST

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Дослідження показників ремонтопридатності засобів для приготування і роздавання кормів

Анотація. Нові наукові та практичні підходи в тваринницькій галузі використовують технології промисловості 4.0 та IoT, зокрема змішувачі-кормороздавачі, для ефективного транспортування та дозування кормів, однак проблеми надійності цих механізмів вимагають досліджень для визначення деталей і вузлів, що обмежують їх працездатність, та розрахунку їх ремонтопридатності. Метою цього дослідження було встановлення конструктивних, виробничих та експлуатаційних відмов механізмів змішувачів-кормороздавачів, причин їх виникнення та часу на їх усунення. Для цього було виконано дослідження змішувачів-кормороздавачів за планом випробувань на надійність [NMT]. План випробувань передбачає наявність N об'єктів, які при втраті працездатності відновлюються M, а досліди зупиняються за досягнення наробітку T. Виконано збирання та обробку вихідної інформації, аналіз емпіричних даних часу усунення відмов змішувачів-кормороздавачів PROFILE 12.2 DS та PROFILE 14.2 DS. В процесі випробувань виявлено, що в гарантійний період експлуатації змішувачів-кормороздавачів, їх несправний стан викликаний відмовами другої групи складності. Були виділені відмови, які пов'язані з відновленням працездатності підсистеми для подрібнення та змішування, який впливає на ремонтопридатність змішувача-кормороздавача. Проведено статистичний аналіз виникнення названих відмов. Визначені основні параметри теоретичного закону розподілу. Зокрема, встановлені показники ремонтопридатності змішувачів-кормороздавачів: середній час відновлення працездатності, $\bar{t} = 24{,}0$ год.; середнє квадратичне відхилення, $\sigma = 12{,}93$ год.; коефіцієнт варіації, $\upsilon = 0{,}49$; теоретичний закон розподілу – закон нормального розподілу. Підтверджено, що середній час відновлення працездатності змішувачів-кормороздавачів за критерієм згоди Колмогорова добре узгоджується із законом нормального розподілу. Розрахунками встановлено, що середній час відновлення працездатності об'єктів досліджень знаходитися в довірних інтервалах: 6,98 год. – нижня довірна межа; 41,02 год. – верхня довірна межа; 34,04 год. – величина інтервалу. Результати можна реалізувати для підвищення ефективності технічного обслуговування і ремонту обладнання на тваринницьких фермах, оптимізації запасів запасних частин

Ключові слова: змішувач-кормороздавач; експлуатаційна надійність; напрацювання на відмову; час відновлення працездатності; механізм подрібнення-змішування

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Design and optimisation of automated hydraulic gate control systems for flood control

Abstract. The study was conducted to analyse the design and optimisation of automated hydraulic gate control systems for effective flood control. It used data analysis from water level sensors, modelling of hydraulic systems, and control algorithms to automate the monitoring of hydraulic locks. As a result of the study, key aspects that confirm the importance of automation of hydraulic gate control for effective flood control were identified. It was established that the introduction of radiofrequency and ultrasonic sensors for water level monitoring provided a high level of data accuracy, which allowed responding in a timely manner to rising water levels. Adaptive control algorithms allowed optimising the operation of gates in dynamic conditions, considering changes in hydrodynamic characteristics. In addition, analysis of gate stability showed that the use of modern materials, such as high-strength steels and composites, substantially increased their durability and corrosion resistance. This was an important factor in ensuring the reliable operation of structures in extreme conditions. The examined models of the dynamic behaviour of gates identified critical zones that are subject to special attention during design since they can be destroyed under the influence of hydrodynamic forces. Overall, the results of the study highlighted the importance of integrating modern technologies into the design of hydraulic systems to improve their functionality and reliability in flood-risk situations. The influence of vibrations and resonant phenomena on the gate structures was analysed, which allowed identifying possible risks for their stability in flood conditions. As a result, recommendations for gate design included structural improvements that help reduce dynamic loads and improve their ability to withstand extreme hydrodynamic conditions

Keywords: water level sensors; algorithms; hydrodynamic pressure; weather forecasting; dynamic behaviour

INTRODUCTION

The relevance of research on automated hydraulic gate control systems for flood control is growing due to climate change and an increase in the frequency of extreme weather events. Floods, which can cause substantial damage to infrastructure, residential areas, and ecosystems, require rapid and accurate responses to reduce negative impacts. Modern automation technologies, in particular, the use of water level sensors, actuators, and control algorithms, provide the possibility of timely adjustment of the operation of hydraulic valves. This not only increases their efficiency in their work but also reduces the risk of accidents, which can be critical in a crisis environment. In the context of the growing challenges associated with global warming, research in this area is becoming urgent to ensure public

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safety and protect the environment. Thus, the analysis and optimisation of such systems are important steps towards improving water management.

In the field of automated hydraulic gate control systems under study, the problem of flood response efficiency is urgent. M. Krichen *et al.* (2024) investigated the introduction of the latest water level sensors to improve the accuracy of flood monitoring. Their results showed that the use of such technologies allowed for a quick response to changes in the water level and reduced the risk of accidents. Y. Song *et al.* (2022) focused on adaptive control algorithms that optimised the operation of hydraulic valves under variable loads. They determined that such algorithms substantially improved the effectiveness of crisis management. D. Bazarov *et al.* (2022) examined the mechanical characteristics of gates and their resistance to hydrodynamic pressure in extreme weather conditions. Their study confirmed that properly designed structures were able to withstand substantial loads without losing functionality. B. Li *et al.* (2022) developed dynamic modelling methods for predicting the behaviour of control systems in real-world conditions. This allowed identifying potential problems and optimising the gate design to improve their performance. F. Piadeh *et al.* (2022) investigated the effect of integrating weather forecasting systems on the efficiency of hydraulic system management. They established that timely information about possible floods substantially increased the level of preparedness and reduced negative consequences.

Y. Hassani & S.M.H. Shahdany (2021) analysed the economic feasibility of implementing automated systems in comparison with traditional methods. Their results showed substantial savings in funds and resources as a result of automating management processes. J. Skowrońska *et al.* (2021) emphasised the importance of choosing corrosion-resistant materials to improve the durability of gates. In their paper, it was noted that the use of such materials could substantially reduce maintenance costs. Q. Zhang *et al.* (2021) considered various approaches to monitoring hydraulic systems in real-time. They noted that modern technologies have substantially improved the quality of data collection and analysis. H. Zhang *et al.* (2022) investigated methods for increasing the resistance of hydraulic valves to changes in the water level. The results of their study proved that improved structures were able to provide reliable protection even during severe floods. L. Cea & P. Costabile (2022) examined the impact of climate change on flood frequency and intensity, which emphasised the importance of management automation. Their results showed the need to adapt existing systems to new environmental challenges. However, there are gaps that require further study, in particular, insufficient attention to the integration of weather forecasting systems and cost analysis for the implementation of such systems, which limits their widespread use in real-world conditions.

The purpose of the study was to identify and evaluate possible ways to optimise the operation of automated hydraulic gate control systems in flood conditions, aimed at improving their efficiency and reliability. Objectives of the study:

1. Learn how to automate hydraulic gates to improve their efficiency during floods.
2. Investigate the influence of modern water level sensors on the accuracy of monitoring.
3. Consider the various technologies used to automate management processes.

MATERIALS AND METHODS

The study analysed the design and optimisation of automated control systems for hydraulic locks, which are critical for ensuring the safety of water structures during extreme weather conditions. The analysis was conducted in the context of hydraulic system management, in particular, in flood risk conditions. For this purpose, various types of sensors that provide accurate and timely monitoring of the water level were considered. Among the most common types of water level sensors were radiofrequency, ultrasonic, and strain gauges.

The study also focused on collecting data from these sensors, enabling real-time water level monitoring systems. The data received from the sensors was transmitted to a central controller or server, where it was processed and analysed. The use of special software, such as Supervisory Control and Data Acquisition (SCADA), allowed visualising information in the form of tables, which simplified monitoring, and decision-making. The study also considered various execution mechanisms used in automated hydraulic lock control systems. It was analysed that electrical, hydraulic, and pneumatic mechanisms are the most common automation options. Each of these types has its own advantages and disadvantages, and specific applications. An important aspect of automated hydraulic lock monitoring systems was the effective interaction between water level sensors and actuators. The sensors provided water level data, which was then analysed by the control system. Based on the data obtained, the actuators automatically adjusted the position of the locks to prevent overflow or ensure optimal water balance. The development of control algorithms based on sensor data, which are a necessary condition for the effective operation of such systems, was also investigated. These algorithms not only determine how valves should respond to changes in water levels but also optimise the overall operation of hydraulic systems, especially under high loads. Algorithms may vary depending on the complexity of the system and the requirements for its operation. The simplest algorithms are "threshold" algorithms that activate the closing or opening of locks when certain water levels are reached.

The study also focused on evaluating the stability of hydraulic structures in extreme conditions, such as heavy rains or rapid snowmelt. Analysis of hydrodynamic forces that occur during floods helped to identify possible problems in the structure and make adjustments to its design. Various sources of information, including scientific and technical literature, technical documentation, data on real systems and experimental results, were used to provide a comprehensive analysis of automated hydraulic gateway control systems. This included scientific and technical literature on the design and optimisation of automated hydraulic gate control systems (Desnanjaya & Nugraha, 2021; Bai *et al*., 2021; Vignesh *et al*., 2024). The papers devoted to both general aspects of automation in extreme weather conditions and special methods of controlling hydraulic structures were analysed. Technical documentation for various types of sensors (radiofrequency, ultrasonic, strain gauge) used for monitoring the water level in automated systems (Júnior *et al*., 2021; Delgado *et al*., 2021; Pramanik *et al*., 2022) was also considered. This allowed examining their technical characteristics, efficiency, and adaptability in different environments.

Data on real automated control systems for hydraulic locks are collected on the basis of implemented projects on water bodies where modern technologies are used for flood control (Quaranta *et al*., 2023; Pan *et al*., 2023). This allowed evaluating the effectiveness of existing solutions and proposing new optimisation approaches; experimental and simulation data obtained during testing of control algorithms and hydrodynamic models (Farajvand *et al*., 2021; Lei *et al*., 2022). This data helped analyse how different types of mechanisms and sensors respond to changes in water levels during floods. This information base provided a comprehensive approach to the study of automated hydraulic lock control systems, considering both theoretical and practical aspects.

RESULTS

The design and optimisation of automated hydraulic gate control systems for flood control is a critical area for ensuring the safety and efficiency of water structures during extreme weather conditions. This allows quickly responding to rising water levels and controlling flood flows to protect settlements and territories. Managing hydraulic systems, especially in flood-risk environments, requires accurate and timely monitoring of water levels. For this purpose, various types of sensors are used, which provide the necessary information for decision-making. Among the most common types of water level sensors are radiofrequency, ultrasonic, and strain gauge (Quaranta *et al*., 2023; Pan *et al*., 2023).

Radiofrequency sensors operate on the basis of the principle of radio frequency identification. They typically use radio waves to measure the distance to the surface of water. This method is characterised by high accuracy and speed. Radiofrequency sensors have no moving parts, which ensures their reliability in conditions of high humidity and pollution. However, their effectiveness may be reduced due to signal reflection from objects on the water surface or interference in the environment. Ultrasonic sensors are one of the most common devices for measuring water levels. They emit ultrasonic waves that bounce off the surface of the water and return to the sensor. The time required to return the signal is used to calculate the distance to the water surface. Ultrasonic sensors provide high accuracy and can be used in a variety of environments. However, they can also be sensitive to external conditions such as air temperature, humidity, and the presence of particles in the air (Fernández-Nóvoa *et al*., 2024).

Strain gauges, also known as hydrostatic sensors, measure water pressure at a certain depth. They are installed at the bottom of the reservoir and respond to changes in the water level by measuring the pressure created by the water column. This type of sensor is highly sensitive and accurate but requires regular maintenance and calibration. Strain gauges are particularly useful in cases where monitoring the water level at great depths is needed (Júnior *et al*., 2021; Delgado *et al*., 2021; Pramanik *et al*., 2022). By collecting data from these sensors, water level monitoring systems can operate in real-time (Table 1). Data received from sensors are transmitted to a central controller or server, where they are processed and analysed. The use of special software allows visualising information in the form of graphs or tables, which facilitates monitoring and decision-making.

Table 1. Sensor parameters for water level monitoring

Sensor type	Measuring range (m)	Accuracy (%)	Response time (s)
Radiofrequency	0-10	1.5	0.5
Ultrasonic	0-15	1	0.3
Strain gauge	0-20	0.5	0.1

Source: compiled by the authors based on M.A. Rahu *et al*. (2022)

Data acquisition systems can be integrated with automatic hydraulic gate control systems. This allows quickly responding to changes in the water level, which is extremely important for flood prevention. In addition, modern technologies allow implementing remote monitoring, which provides convenience and efficiency of management. The use of various types of water level sensors, data collection, and processing systems, is a critical element in the management of hydraulic systems. This not only improves the accuracy of monitoring but also provides a timely response to flood risks, which in turn contributes to improving public safety and environmental protection. Automation of hydraulic gate control in flood control systems requires the use of efficient actuators. They provide automatic adjustment of the gate position according to data obtained from water level sensors (Akiyanova *et al*., 2023). Among the most common mechanisms are electric, hydraulic, and pneumatic. Each of these types has its own advantages and disadvantages, and specific applications.

Electric actuators are one of the most common automation options. They operate on the basis of an electric drive that activates the gate mechanism. This type of mechanism has a number of advantages, in particular, high control accuracy and speed of response. Electrical mechanisms are easily integrated into automatic control systems, making them ideal for use in environments where a fast and accurate response to changes in water levels is required. However, electrical mechanisms may have limitations in conditions of high humidity or extreme temperatures. In addition, their effectiveness may decrease under high loads or in case of mechanical damage. Therefore, for critical systems, such as floodgate control, electrical mechanisms can be supplemented with other types.

Hydraulic actuators use fluid pressure to control the position of the gate valves. They are characterised by high strength and the ability to withstand heavy loads, making them ideal for use in environments where substantial power is required. Hydraulic systems also ensure smooth operation, which is important for precise adjustment. However, hydraulic mechanisms require complex support systems, in particular, pumps and tanks, and regular maintenance to prevent fluid leakage and component wear (Fakher *et al.*, 2021). On the other hand, their ability to operate in extreme environments makes them valuable in systems where electrical mechanisms may be inefficient.

Pneumatic actuators use compressed air to adjust the gate valves. They respond quickly to changes in the system and can be lightweight and compact, making them convenient for use in confined spaces. Pneumatic systems can also be relatively easy to maintain and do not require complex fluid systems, which reduces the risk of leaks. However, pneumatic mechanisms are usually less powerful than their hydraulic counterparts and may be less efficient under high-pressure conditions. They can also be sensitive to changes in temperature and humidity, which can affect their performance. A key element of the automated hydraulic gate control system is the effective interaction between water level sensors and actuators. The sensors provide water level data, which is then analysed by the control system. Based on the data obtained, the actuators automatically adjust the position of the gate valves to prevent overflow or ensure optimal water balance (Desnanjaya & Nugraha, 2021; Bai *et al.*, 2021; Vignesh *et al.*, 2024).

The systems can be configured for different operating modes depending on the conditions, for example, if the water level rises to critical levels. In such situations, the actuators can immediately close the shutters to prevent flooding, providing a quick response to changing conditions. The choice of the type of actuator and its integration with sensor systems is critical to ensuring the efficiency of automated hydraulic gate control systems. The ability of these systems to respond quickly to changes in the environment is key to successful flood control and reducing risks to the population and infrastructure. Automatic hydraulic gate control is a critical aspect in flood control systems. The development of control algorithms based on sensor data is a prerequisite to ensure the effective operation of such systems (Zhang *et al.*, 2023). These algorithms not only determine how gates should respond to changes in water levels but also optimise the overall operation of hydraulic systems, especially under high load conditions.

The main purpose of control algorithms is to provide a timely and accurate response to data received from water level sensors. Algorithms may vary depending on the complexity of the system and the requirements for its operation. The simplest are "threshold-based" algorithms that activate closing or opening gates when certain water levels are reached. More complex algorithms may include control logic that considers the dynamics of water level changes, the rate of rise or fall, and forecasts based on historical data. For example, the algorithm can analyse data from multiple sensors to provide more accurate decisions about the time and magnitude of opening or closing gates. Using mathematical models, such as regression analysis or artificial intelligence-based models, can substantially improve the efficiency of decision-making. In high-load environments, such as heavy rains or floods, control systems should operate with maximum efficiency. Optimising the operation of hydraulic systems requires considering many factors, such as the flow rate, the volume of incoming water, and the state of infrastructure. Algorithms can use optimisation principles that allow achieving a balance between response speed and control accuracy. For example, if a large volume of water enters, the algorithm can increase the opening speed of the gate to avoid overflow, while controlling the likelihood of negative consequences, such as erosion or collapse of structures. For this purpose, mathematical modelling methods can be used to predict the results of actions and adapt real-time management strategies.

The variability of natural conditions, such as different rain intensities or snowmelt rates, requires flexibility in control systems. Adaptive algorithms become extremely important in this situation, as they can automatically adjust their parameters depending on changes in the environment. These algorithms can include machine learning mechanisms that allow the system to learn independently from new data. For example, if the algorithm detects that the water level is rising faster than predicted, it can adapt its response by increasing the frequency of data updates or changing thresholds to control the gate. This incre ases the flexibility of the system, reduces the risk of flooding, and prevents overloading of infrastructure elements.

Hydraulic closures are vital elements of water management systems, especially during floods. The stability of these structures in extreme conditions, such as heavy rains or rapid snowmelt, is crucial to prevent their destruction and ensure environmental safety (Zoffoli *et al.*, 2023). It is necessary to use effective methods for assessing the stability of structures and consider the influence of hydrodynamic forces to do this. Hydraulic gate stability assessment can be performed using a variety of methods, including analytical, numerical, and experimental approaches. Analytical methods are based on mathematical models that describe the behaviour of structures under the influence of loads. The main ones include calculation methods based on the theory of elasticity and fluidity, which allow estimating how gates respond to water loads. These models can help identify potential risk areas, such as local stresses or deformations. Numerical methods, in particular, finite element methods (FEM), allow for a detailed analysis of gate stability, considering complex geometric shapes and materials. Due to these methods, it is possible to visualise the distribution of stresses and deformations in the structure, which allows identifying critical zones that can be subject to destruction under the influence of hydrodynamic forces. Experimental methods, in turn, involve physical tests on gate models, which can provide valuable information about their behaviour in real-world conditions. Tests in the laboratory or in the field allow observing factors that are difficult to simulate, such as fluctuations in water levels, current velocity, or exposure to foreign objects (Farajvand *et al*., 2021; Lei *et al*., 2022).

Hydrodynamic forces that occur during floods are one of the main factors affecting the stability of hydraulic gates. The main components of hydrodynamic forces are hydrostatic pressure, hydrodynamic forces, and vibrations and fluctuations. Hydrostatic pressure is the pressure created by a column of water above the gate, and it increases with depth. At high water levels, the hydrostatic pressure can exceed the permissible values, which leads to deformation or even destruction of the structure. Hydrodynamic forces arise due to the movement of water, in particular, during a rapid flow or disturbance of water (waves, swirls). These forces can act on gates with different directions and values, making them difficult to estimate. They can cause additional loads on the structure, which can lead to its destruction. During floods, substantial vibrations can occur in the structure due to water disturbances. This can lead to material fatigue and reduced gate stability. It is necessary to conduct a comprehensive analysis of the effect of hydrodynamic forces to ensure the proper stability of hydraulic valves. Calculations performed using analytical and numerical methods can help identify possible problems in the design and make adjustments to its design.

Hydraulic closures are critical elements of water management systems, especially during extreme natural events such as floods (Yasmin *et al*., 2022). The dynamic behaviour of gates during water fluctuations and load changes is an important aspect that requires detailed analysis. The examination of vibrations and dynamic loads affecting gate structures allows developing effective control methods and ensuring their stability in natural disasters. Gate fluctuations can be caused by a variety of factors, including changes in water level, flow rate, and other hydrodynamic phenomena. These fluctuations can lead to substantial dynamic loads that negatively affect the integrity of the structure. Dynamic loads on gates can be either static or dynamic (Table 2). Static loads are caused by hydrostatic water pressure, which increases with depth. Dynamic loads, in turn, occur due to the movement of water, disturbances, waves, and other factors that cause fluctuations.

Table 2. Analysis of dynamic gate loads

Operating conditions	Hydrodynamic forces (kH)	Vibrations (m/s²)	Destruction risks (%)
Normal	50	5	10
During a flood	120	15	30
Extreme conditions	200	25	50

Source: compiled by the authors based on S. Kim *et al*. (2023)

Various methods are used to examine these phenomena in detail. These include analytical models that allow determining the theoretical values of vibrations and gate loads using mathematical equations describing fluid mechanics and structural statics. Numerical methods, in particular, finite element methods (FEM), are used to model dynamic gate loads in real-world situations. These models consider all possible factors, such as pressure changes, flow rates, and vibrations. Experimental methods include physical tests on gate models under controlled conditions, which allows investigating the real dynamics of structures under the influence of various loads. Modelling the dynamic behaviour of gates during floods is an important tool for predicting their performance in extreme conditions. Modern computer programmes that use numerical modelling methods make it possible to create detailed models of hydraulic valves that reflect their behaviour during vibrations.

In the modelling process, it is important to consider hydrodynamic forces, analysing how the flow rate and water level change over time, it is possible to predict how these factors will affect the dynamics of gates. The interaction between the gate and the water environment is also important to consider, as it is necessary to understand how the gate design interacts with water, in particular, how fluid disturbances affect the stability and stability of the structure. In addition, vibrations and resonance are critical aspects, since vibrations can cause resonant phenomena that can lead to catastrophic consequences. Modelling such effects is crucial for understanding how a structure can withstand dynamic loads. Models that consider these factors allow developing strategies to improve gate stability. In particular, knowledge of dynamic behaviour can help in selecting materials, designing structures, and creating automatic control systems that respond to changes in real-time (Table 3).

Table 3. Influence of modern materials on the durability of gates

Material type	Corrosion resistance (%)	Durability (years)	Expenses (UAH/m²)
High-strength steel	85	30	800
Composite	90	25	1200
Ordinary concrete	75	15	500

Source: compiled by the authors based on M. Issaoui *et al*. (2022)

The design of hydraulic gate structures is an important component in water management systems, especially in conditions where the risk of flooding and other extreme natural phenomena is becoming increasingly relevant (Nowak *et al*., 2022). It is necessary to consider various design criteria and use modern materials and technologies that can increase their strength to ensure the reliability and efficiency of gates in such conditions. When designing hydraulic valves, it is important to follow several basic criteria. Gate structures must be designed to withstand hydrostatic and hydrodynamic loads. The maximum water pressure values that can occur during flooding, as well as possible vibrations and vibrations that can affect the stability of structures, are considered to do this. The choice of materials used in the structure should ensure their resistance to corrosion, fatigue, and other destructive processes. Modern building materials, such as high-strength steels, composites, and special concrete mixes, can provide the necessary strength and service life. In the event of changes in conditions associated with rising water levels or changes in the environment, structures must be able to adapt. This may include the modularity of the gates or the possibility of their refinement during operation. Structures must be designed with environmental impact in mind. This includes not only the selection of environmentally friendly materials but also an assessment of the impact on ecosystems and the possibility of returning to the natural environment after their operation is completed.

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DISCUSSION

In the course of the study on the design and optimisation of automated hydraulic gate control systems for flood control, it was determined that the integration of modern technologies in the management of such systems substantially increases their efficiency. The results showed that the introduction of radiofrequency and ultrasonic sensors for monitoring water levels enables a high level of data accuracy. This, in turn, allowed responding in a timely manner to changes in hydrodynamic conditions, which is critical during floods.

This problem was also investigated by J. Zaczek-Peplinska & L. Saloni (2023), where the results confirmed that the integration of modern technologies in the management of hydraulic systems, in particular, automation, has a substantial impact on the effectiveness of flood control. Automated control systems allow responding more quickly to changes in hydrological conditions, which reduces the risk of flooding and contributes to the efficient use of resources. Due to the introduction of intelligent algorithms, it is possible to anticipate potential threats and ensure the safe operation of hydraulic gates. A study by Y. Li *et al.* (2023) also showed that automation of hydraulic gate control systems during emergencies also improves the accuracy and reliability of the process. The use of modern sensors and monitoring systems allows getting real-time data on the state of water, which is critical for decision-making (Kabdoldina *et al*., 2022). This, in turn, helps to reduce the negative consequences associated with floods and ensures better management of resources in crisis situations. Notably, the automation of hydraulic system control not only increases the efficiency of emergency response but also optimises the work of personnel. Automated control systems free specialists from routine tasks, allowing them to focus on the strategic aspects of management and planning (Honcharenko *et al*., 2023). However, it is also important to consider the potential risks associated with technological failures or cyber-attacks that may threaten the security of water resources and require careful monitoring and protection.

Adaptive control algorithms have demonstrated their ability to optimise gate operation in dynamic conditions. The study showed that algorithms that consider changes in hydrodynamic characteristics can substantially improve the efficiency of automated systems. With this adaptability, the system can quickly adjust the operating mode of the gates, reducing the risk of flooding and damage. S. Cvejić *et al.* (2024) concluded that optimising the operation of hydraulic valves in response to changes in hydrodynamic characteristics is a key element in reducing the risk of flooding. Adaptive control systems that consider changes in water flows, pressure and other critical parameters allow you to adjust the position of the valves in a timely manner. This not only increases the efficiency of water disposal but also ensures the stability of the environment, reducing the possibility of environmental disasters. H. Albo-Salih & L. Mays (2021) determined that real-time hydraulic gate control using data from modern sensors and monitoring systems substantially improves flood response. Due to the analysis of input data, specialists can quickly make informed decisions about opening or closing gates, adapting their operation to changing conditions. This allows ensuring the safety of settlements and reducing the cost of flood relief, creating a more efficient water management system.

These results confirm the above study, as they demonstrate that the integration of modern technologies into the hydraulic gate control system substantially improves the response to changes in hydrodynamic characteristics. They also show that automation and the use of real-time data can reduce emergency response times, which is crucial for preventing flooding. In addition, the results point to the need for further development and improvement of technological solutions to ensure greater stability of systems in extreme weather conditions. Analysis of gate stability has shown that the use of modern materials, such as high-strength steels and composites, has a positive effect on their durability and corrosion resistance. This confirms the importance of choosing the right materials in the design of structures that must withstand extreme loads during floods (Moldabayeva *et al.*, 2021). As a result of the study, it was recommended to use materials that have high resistance to destruction, which helps to increase the reliability of structures.

The paper of J.N. Aslanov *et al.* (2022) is also notable, who emphasised that modern materials such as high-strength steels and composites play an important role in the choice of structural materials to improve the durability of hydraulic gates. The use of these materials contributes to lighter and stronger structures that can withstand substantial mechanical loads and corrosion influences. This is especially true in environments where hydraulic systems are exposed to extreme temperatures and chemical aggressors, which can reduce their efficiency and safety. In turn, H.A. Ragheb *et al.* (2021) concluded that the effectiveness of high-strength steels and composites in ensuring the reliability of structures under extreme conditions also confirms their ability to adapt to various operating scenarios. Using modern processing and manufacturing technologies leads to these materials providing a high level of resistance to mechanical damage and endurance in conditions of load fluctuations. This, in turn, increases the durability of hydraulic valves and reduces maintenance and repair costs, which is an important factor in water management systems. These data are consistent with the theses given in the previous section, as they confirm the importance of choosing modern structural materials to ensure the durability of hydraulic valves. High-strength steels and composites not only increase mechanical stability but also reduce the risk of damage under extreme conditions, increasing the overall efficiency of the system (Abdykalykov *et al.*, 2024). Therefore, investing in the latest materials can substantially reduce operating costs and improve the reliability of hydraulic structures in the long term.

The analysis of the dynamic behaviour of gates has shown that critical zones that are subject to special attention during design can undergo substantial destruction under the influence of hydrodynamic forces. The results confirmed that it is important to conduct a comprehensive assessment of such structures to identify potential problems and make adjustments during the design phase. This allows avoiding catastrophic consequences during floods and ensuring the long-term operation of the systems. S. Bhattacharjee *et al.* (2021) also conducted a study, the results of which confirmed that identifying vulnerabilities under the influence of hydrodynamic forces is crucial for developing effective risk management strategies in the design of hydraulic gates. Analysing data on loads that can occur during floods can identify potential weaknesses in structures that can lead to their destruction or inefficiency. Focusing on these vulnerabilities provides an opportunity to improve design solutions and improve the overall stability of gates. M.V. Varkey & M.P. Philbin (2022) also established that risk and problem analysis in gate design also contribute to the development of innovative technologies that can help strengthen structures. For example, the use of computer modelling and hydrodynamic calculations provides for the accurate prediction of the gates' behaviour under various loads (Momynkulov *et al.*, 2023). This, in turn, allows engineers to consider specific operating conditions and optimise structures to improve their reliability in changing conditions, in particular, during extreme weather events. Comparing the data obtained in the course of the study, it can be concluded that an integrated approach to the design of hydraulic valves is important. The results show that identifying vulnerabilities and carefully analysing risks are vital elements for ensuring the sustainability of structures during floods. This highlights the need to integrate state-of-the-art technologies, such as computer modelling, into the design process to better respond to potential threats and ensure the long-term reliability of hydraulic systems.

The study also drew attention to the influence of vibrations and resonant phenomena on gate designs. It is established that vibrations can cause resonant effects that can lead to catastrophic consequences. Knowledge of these phenomena has become the basis for developing recommendations for improving structures that help reduce dynamic loads and improve their stability. Z. Guo *et al.* (2023) concluded that the effect of dynamic loads on the stability of hydraulic gates is an important aspect that requires detailed analysis in the design of such structures. During floods, the gates are subjected to substantial vibrations that can cause resonance, leading to mechanical damage or even destruction (Homon *et al.*, 2023). Identifying these risks allows engineers to develop more reliable solutions that can withstand the extreme conditions that occur during intense hydrodynamic processes. P. Deng *et al.* (2024) state that studies analysing dynamic loads help identify critical parts of the structure that require additional reinforcement or modification. An important step is to use computer simulations to simulate the behaviour of gates under various conditions to predict potential problems. This approach provides more effective risk management, increasing the reliability of hydraulic systems and reducing the likelihood of negative consequences during emergencies.

When analysing the results of the study, it is clear that dynamic loads and fluctuations substantially affect the stability of hydraulic gates, and ignoring them can lead to serious consequences during floods. Identifying the risks associated with resonance confirms the need to implement specialised design methods that consider these factors. This requires not only the use of the latest technologies for modelling but also constant monitoring and assessment of the condition of structures to ensure their safety and efficiency in all operating conditions. Overall, the results of the study highlighted the importance of integrating modern technologies into the design of automated hydraulic gate control systems. This improves the functionality and also increases their reliability in flood-risk situations. Making changes at the design stage, based on the obtained data, contributes to the creation of more efficient and safe solutions for controlling hydraulic systems.

CONCLUSIONS

As a result of the study, the importance of automation of hydraulic gate control for effective flood control was confirmed. The introduction of radiofrequency and ultrasonic sensors for monitoring the water level provided high data accuracy, which allowed responding promptly to rising water levels. Adaptive control algorithms optimised the operation of gates in dynamic conditions, considering changes in hydrodynamic characteristics. The study showed that the use of modern materials, such as high-strength steels and composites, substantially increases the durability and resistance of structures to corrosion, which is an important factor for their reliable operation in extreme conditions. Analysis of the dynamic behaviour of the gates revealed critical zones that require special attention during design since they can be destroyed by hydrodynamic forces. The risks associated with vibrations and resonant phenomena were also identified, which confirmed the need to take these factors into account in the design process. In general, the results of the study highlighted the importance of integrating modern technologies into the design of hydraulic systems to improve their functionality and reliability in flood risk situations, which ensures more effective control of hydrological processes.

The study also established that the integration of automated control systems improved the response to changes in hydrological conditions. Automation provides fast data processing and decision-making, which is critical during floods when the situation can change in a matter of minutes. The use of adaptive algorithms allowed gates to respond more quickly to rising water levels, reducing the risk of flooding in surrounding areas. The results confirmed that automation systems improve management and contribute to public safety. Thus, the study highlighted the need to develop automated flood control systems. It is necessary to further investigate the impact of climate change on the hydrodynamic characteristics of water resources and their interaction with automated hydraulic gate control systems.

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CONFLICT OF INTEREST

None.

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Проєктування та оптимізація автоматизованих систем керування гідравлічними затворами для боротьби з паводками

Анотація. Дослідження проведено з метою аналізу проєктування та оптимізації автоматизованих систем управління гідравлічними затворами для ефективного контролю паводків. У ньому використано аналіз даних з датчиків рівня води, моделювання гідравлічних систем та алгоритми керування для автоматизації моніторингу гідравлічних шлюзів. В результаті дослідження визначено ключові аспекти, які підтверджують важливість автоматизації управління гідравлічними затворами для ефективного протипаводкового захисту. Встановлено, що впровадження радіочастотних та ультразвукових датчиків для моніторингу рівня води забезпечує високий рівень точності даних, що дозволяє своєчасно реагувати на підвищення рівня води. Адаптивні алгоритми керування дозволили оптимізувати роботу затворів у динамічних умовах, враховуючи зміни гідродинамічних характеристик. Крім того, аналіз стійкості затворів показав, що використання сучасних матеріалів, таких як високоміцні сталі та композити, суттєво підвищує їх довговічність та корозійну стійкість. Це стало важливим фактором забезпечення надійної роботи конструкцій в екстремальних умовах. Розглянуті моделі динамічної поведінки затворів дозволили виявити критичні зони, які підлягають особливій увазі під час проєктування, оскільки можуть бути зруйновані під дією гідродинамічних сил. Загалом, результати дослідження підкреслили важливість інтеграції сучасних технологій у проєктування гідравлічних систем для підвищення їх функціональності та надійності в умовах паводкового ризику. Проаналізовано вплив вібрацій та резонансних явищ на конструкції затворів, що дозволило виявити можливі ризики для їх стійкості в умовах паводків. В результаті надано рекомендації щодо проєктування затворів, які включають конструктивні вдосконалення, що сприяють зменшенню динамічних навантажень та підвищенню їхньої здатності витримувати екстремальні гідродинамічні умови

Ключові слова: датчики рівня води; алгоритми; гідродинамічний тиск; прогнозування погоди; динамічна поведінка

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Modelling the optimal switching scheme of Ukrainian power grids during blackout in one city/region

Abstract. The purpose of the study was to develop effective algorithms and strategies to minimize the negative effects of emergency power outages. A methodology had been developed that defines the steps and processes for efficient modelling and selection of optimal power grid switching schemes that can ensure the stability of power supply and increase grid resilience during blackouts in a particular city or region. As a result of the study, a power grid switching scheme was developed and improved for use in military and other crisis situations. Possible power outage scenarios were studied, which made it possible to consider various response options and ensure maximum efficiency and reliability of power supply during emergencies. Based on the data, and taking into account additional aspects of grid safety and reliability, the optimal power transmission routes and location of backup power sources were determined. In addition, a risk assessment was carried out to ensure stable operation of the system during crisis situations, which helped to increase its resilience to possible failures. The analysis of existing methods, such as manual switching of networks, use of automated systems

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and involvement of backup power sources, allowed us to identify the advantages and disadvantages of each approach to ensure stable power supply during a blackout in one city or region. As a result, it was found that by optimizing the grid switching scheme, the damage caused by blackouts can be minimized. The advantages and disadvantages of the different approaches were also identified, and the results of the study confirmed that the optimal grid switching scheme significantly reduces the duration of the blackout

Keywords: energy resilience; emergency management; backup power supplies; outage analysis; energy crises; load management

INTRODUCTION

Optimization of the power grid switching scheme is aimed at reducing the negative effects of power outages and ensuring rapid restoration of power supply. Optimization involves a thorough analysis of the existing power grid to determine the most efficient power transmission routes. This includes exploring possible options for switching to backup lines or power sources to minimize the time during which power is not available.

The relevance of the study is driven by the risk of frequent or prolonged power outages in Ukraine, which can occur due to a variety of factors, such as natural disasters, technical failures or military operations. Modelling should take these factors into account to ensure reliable power supply restoration. The research problem is the need to create an effective strategy for managing power supply in the face of unforeseen power outages. Different cities and regions may have different types of power grids and infrastructure, which makes it difficult to develop a universal switching model that would be effective in all cases.

One important aspect of optimization is the integration and efficient use of backup power sources, such as diesel generators or battery systems. An optimal switching scheme includes automatic or semi-automatic switching to these reserves in the event of a main source failure. The introduction of modern automated control systems allows for a rapid response to emergencies. Monitoring and control systems can automatically detect outages and instantly activate backup lines, which reduces recovery time. Optimization includes load management to avoid overloading parts of the network that are left without power. This can include temporarily limiting power consumption in certain areas or redirecting the load to less busy areas.

The problem in this area is the significant lack of modern knowledge and technologies required to model various emergency scenarios. S. Verma & T.R. Chelliah (2024) found that a detailed analysis of the potential causes of power outages and the development of comprehensive action plans for each of these cases is necessary. This includes identifying possible sources of problems, assessing their impact on the power system, and creating a rapid response strategy that will ensure that power is restored quickly and efficiently, while T. Yakushkin *et al.* (2023) found that in the event of a power outage, it is critical to ensure uninterrupted supply to key facilities such as hospitals, water utilities, and other critical infrastructure that are vital to the normal functioning of the population. Issues requiring further research include the development of methods to optimize grid switching schemes, which can significantly reduce the impact of power outages on the economy and the lives of the population, ensuring greater stability and faster restoration of electricity supply. Another important task is to analyse the optimal switching scheme that ensures automatic or semi-automatic switching to backup lines or power sources, which can significantly reduce the duration of a power outage. T.G. Grandón *et al.* (2024) and S. Fang *et al.* (2024) analysed and developed conservation strategies, focusing on the fact that one of the key problems of electricity systems is the ageing and deterioration of equipment that has already reached the end of its service life or is approaching the end of its technical life. This significantly complicates the process of optimal management and reduces the efficiency of the system. S. Abbas *et al.* (2024) analysed in detail in their study and established the relationship between the number of used equipment and its susceptibility to breakdowns, failures, and emergencies. They concluded that when equipment is operated beyond its intended lifespan, the risk of malfunction increases, which can lead to serious accidents, longer power outages and threats to the stable operation of the entire system. Gaps requiring further research include impact assessments, which are particularly important for key components such as transformers, generators, cables and other elements of the transmission and distribution system. The need for further research into resilience is that worn-out equipment may operate with less stability, which in turn reduces the overall reliability of the grid. Another important issue in this area is that old equipment leads to more frequent outages, interruptions and lower quality of electricity supply. A. Alberini & N. Umapathi (2024) presented a methodology for determining optimal application rates, which takes into account that with the age of equipment, the need for resources for its maintenance increases. A.V. Soler (2024) & M. Maldet (2023) analysed that the need for regular repairs, replacement of parts and maintenance creates a significant financial burden on grid operators. Different forms of equipment ageing require additional study, as this process often leads to a decrease in performance and reliability, it is important to investigate how different forms of ageing affect the functional characteristics of equipment, and to develop methods to improve its efficiency and extend its service life.

Research in this area indicates that increasing energy losses during transmission and distribution negatively impact overall system performance and can lead to higher tariffs for consumers due to these energy losses. The management of systems containing legacy components is complicated by the need to take into account their instability and possible reliability issues. This requires additional efforts to monitor the condition of the equipment and frequent inspections.

The aim of this study was to develop efficient and adaptive schemes for switching the Ukrainian power grid during a blackout in a particular city or region, which would ensure uninterrupted power supply, reduce outage time and minimize the negative impact on the economy. To achieve this goal, the following tasks were identified: analysing the current state of the power grid and its vulnerabilities, creating models for different blackout scenarios, assessing the effectiveness of existing switching schemes, and optimizing switching processes to reduce outage time and its impact on consumers.

MATERIALS AND METHODS

The study analysed threats and vulnerabilities and developed typologies that allowed to identify and classify key threats to grid security in the event of blackouts, such as increased power outages and reduced system reliability. This allowed to develop targeted strategies for optimizing switching schemes for effective power grid management. The focus was on studying and classifying threats arising from the introduction of various technologies. This included analysing the possible problems and risks associated with energy management during blackouts in individual cities or regions, as well as developing effective solutions to improve system resilience. The threats were classified to formulate recommendations for improving the processes of developing and implementing grid-switching schemes. This included a comparative analysis of different scenarios and control technologies, as well as the establishment of benchmarks for performance evaluation. The study covered the evaluation of various technologies for optimizing grid-switching schemes. This included studying automatic and semi-automatic switching options and analysing the efficiency of backup power sources, such as diesel generators, battery systems and gas turbine generators. Particular attention was paid to methods that could ensure rapid restoration of power supply. In addition, the study included the development of recommendations for improving energy management to minimize economic losses.

Key characteristics were assessed, such as the effectiveness of different grid switching schemes, including automatic and semi-automatic systems. Each technology was assessed in detail for its resilience to known challenges, such as the slowdown in the deployment of new systems, the increase in the capacity of energy facilities and the growing competition among energy companies due to the transition to a balancing electricity market. It was assessed the possibilities of preventing and detecting emergency power outages in various scenarios. This included the development and testing of algorithms and protocols for automatic and semi-automatic switching of power grids. Particular attention was paid to the creation of monitoring systems and management interfaces that ensure a quick response to unforeseen situations. It also included an analysis of safety protocols, maintenance procedures, and the integration of new technologies and tools to improve efficiency (Salau *et al.*, 2020; Panda & Das, 2021). A key aspect was to compare the impact of each technology on an important task: improving the system of optimal management of active power flows in electricity systems. This became the basis for developing methods that improve management processes. Delays in the implementation of various technologies were analysed, and the efficiency and reliability of power systems, including Smart Grid technologies, were assessed. Particular attention was paid to assessing the effectiveness of solutions such as automated control systems (Schneider Electric), software tools for modelling power grids, and devices for operational control (Siemens). The project specifications, requirements, and risk level were taken into account when selecting the modelling technologies. This included automated control systems such as GE Digital Energy, monitoring devices from Honeywell Process Solutions, and blackout simulation software such as DIgSILENT PowerFactory.

RESULTS

Modern technologies aimed at improving the efficiency and reliability of energy systems, including Smart Grid technologies, play an important role in the development of the electricity sector. The introduction of these technologies into Ukraine's power system could be a key step towards the country's integration into the European energy community and market. The use of Smart Grid will allow for more flexible management of energy resources, increase security of supply, reduce energy losses, and promote the development of renewable energy sources, which is important for achieving energy independence and stability.

As a result of large-scale military operations, occupation and massive missile attacks on the energy infrastructure, Ukraine has lost more than 40% of its generating capacity. This resulted in a technically outdated system of centralized electricity generation and distribution that was unable to respond effectively to such challenges. At the end of November 2022, the country's unified energy system experienced its first large-scale blackout, and by March 2023, the capacity deficit reached a critical level of 4.5 GW. This situation has highlighted the need to modernize the power system, introduce new technologies to increase infrastructure resilience, and diversify energy sources to ensure a reliable energy supply in the face of external threats (Eslahi *et al.*, 2021).

Voltage control in power grids is an important aspect that requires compliance with technical standards of electricity quality in accordance with applicable regulations. This not only ensures the stability of power supply parameters, but also increases the overall economic efficiency of power grids and electricity consumers. Voltage regulation helps to avoid overloads, reduce power losses and ensure the smooth operation of enterprises and organizations, which is especially important in today's economy with its increased requirements for the reliability of power supply.

According to the Energy Strategy of Ukraine until 2035, the main direction of development of the Ukrainian energy sector is the integration of the integrated power system of Ukraine into the European association of electricity transmission system operators. This creates a need to solve a number of technical problems related to the assessment of the performance parameters of the integrated power system of Ukraine and ensuring their compliance with European energy standards. One of the key parameters is the frequency, which directly affects the operation of the entire power system, and determines its stability and quality of operation. Research and optimization of frequency is essential to ensure reliable electricity exchange and synchronization with the European power system (Zubko, 2024).

Smart Grid technologies ensure the integration of various elements of the power system through intelligent information networks, which allows for more efficient coordination of electricity generation, transmission, and consumption. The use of modern information technologies in the management of energy flows contributes to the reliability and stability of electricity supply, reduction of electricity losses, and full integration of renewable energy sources into the overall system. For Ukraine, where the energy infrastructure requires significant upgrades, the introduction of Smart Grid technologies is not only appropriate, but also a critical step to ensure reliable, cost-effective and environmentally sustainable operation of the power system, which will reduce dependence on traditional energy sources and bring the country closer to European energy standards.

Automated control systems, such as those from Schneider Electric, play an important role in ensuring the efficiency and resilience of power systems during blackouts. They integrate with Smart Grid technologies to monitor and manage energy flows in real time, which helps to optimize energy consumption and reduce the risk of downtime. This allows for quick response to faults and increases the flexibility of systems in the face of change.

GE Digital Energy can play an important role in modelling the optimal switching scheme for Ukraine's power grids during blackouts. This energy management automation system improves the reliability and efficiency of power grids. Integration with Smart Grid technologies allows for optimized energy distribution and faster response to changes in energy demand, which is critical in blackout situations. Monitoring technologies similar to those of Honeywell Process Solutions can be used to model the optimal switching scheme for Ukraine's power grids during blackouts. They provide high measurement accuracy and data collection and analysis capabilities, which is important for ensuring the efficiency and reliability of power systems in extreme conditions.

The DIgSILENT PowerFactory software can play an important role in modelling the optimal switching scheme for power grids during blackouts. It is a tool for simulating electrical systems that allows analysing their stability and performance in crisis situations. In particular, the blackout scenario modelling capabilities help engineers investigate the system's response to emergencies and identify critical components that affect the grid's stability.

Even before 24 February 2022, Ukrainian scientists and energy experts were actively calling for the large-scale deployment of renewable energy sources, emphasizing the importance of decentralizing power generation. According to studies conducted by the State Agency on Energy Efficiency and Energy Saving of Ukraine, the technically available potential for energy production from renewable sources and alternative fuels is estimated at 98 million tonnes of fuel equivalent per year (Mokred & Wang, 2024). This indicates the country's significant potential to reduce dependence on traditional energy sources and increase energy security through diversification of energy sources and localization of production.

According to current standards, the voltage in power grids must remain within acceptable fluctuations (Qu *et al.*, 2023). Significant deviations from these limits can damage sensitive electronic equipment and cause disruptions in the operation of power supply systems. To prevent sudden voltage surges or drops, voltage regulators are used to ensure that voltage parameters are stable and within acceptable limits. This is especially important for ensuring the reliable operation of critical infrastructures and energy efficiency.

Deviations from the permissible limits can cause serious emergencies, cascading blackouts and destabilization of the Integrated Power System of Ukraine, which can lead to significant technical and economic losses (Shahini *et al.*, 2024). Frequency regulation is a complex automatic control task in any power system. Continuous progress in the field of engineering and technology, as well as the improvement of control methods and means, make this task constantly relevant. The importance of optimizing frequency control and power flows in power systems is growing along with the increasing share of renewable energy sources, which adds new challenges to ensure the stability and reliability of power supply (Kubatko *et al.*, 2024).

In conformity with the Ministry of Energy of Ukraine for 2021, even before the outbreak of war, 61% of the main equipment of power substations, such as power autotransformers, transformers, measuring transformers and switches, had exhausted their estimated technical life of 25 years or more. In addition, 13,000 kilometres of 220-330 kV overhead power lines have been in operation for more than 40 years, which is 64.45% of the total length. Due to significant wear and tear, 1,124 kilometres of 220-800 kV lines (4.95% of the total length) required complete replacement or reconstruction. The condition of distribution grids also remained critical, with 316,000 kilometres of 0.4-110 kV overhead lines and 24,000 kilometres of 0.4-35 kV cable lines requiring major repairs, reconstruction, and replacement. This significant deterioration of the infrastructure threatened the reliability of the power supply and required urgent investments to modernize and maintain the uninterrupted operation of the power system. The adopted Law on the Electricity Market was intended to allow power plants with a capacity of up to 20 MW to be connected to distribution networks as distributed generation. However, in practice, solar power plants and wind power plants were built and benefited from the green tariff, but their capacity corresponded to the category of large plants (from 50 MW to 300 MW). As a result of the lack of a clear definition of the term "energy exchange" in the legislation, small (5 kW-5 MW) and medium-sized (5-50 MW) generating capacities were at a disadvantage in a market dominated by large monopolists. This created serious obstacles to the development of competition, as small and medium-sized producers could not compete adequately due to a lack of market access and the necessary support mechanisms.

An important task remains to improve the legislation to create fairer conditions for all market participants, which will facilitate the development of the energy sector and the integration of renewable energy sources (Kubatko *et al*., 2024).

Voltage regulation has a significant impact not only on the quality of electricity supply, but also on the efficiency of production processes at industrial enterprises. The correct voltage level ensures stable operation of equipment, reduces the likelihood of damage and prevents disruptions in technological processes. This, in turn, helps to increase productivity, reduce repair and maintenance costs, and improve the overall energy efficiency of production facilities. Effective voltage regulation can also have a positive impact on the quality of end products, as stable electrical parameters help to avoid defects caused by voltage fluctuations. Therefore, ensuring an appropriate level of voltage regulation is critical for the sustainable development of the industrial sector.

Ukraine's energy sector is undergoing significant changes due to the reorganization of the energy market, which increases the importance of ancillary services, including frequency regulation. At the same time, there is a stable trend of increasing the share of renewable energy sources in the total generating capacity of the Integrated Power System of Ukraine. This affects the power balance in the power system and requires the introduction of new approaches to frequency control. Taking into account natural fluctuations in renewable energy generation, such as changes in wind and solar resources, it becomes necessary to develop effective mechanisms for integrating these sources into the existing power system. This includes not only the modernization of existing technologies, but also the introduction of new energy storage systems, the expansion of energy services and the improvement of interaction between consumers and producers of electricity. Such steps will not only improve the stability of the energy system, but also contribute to the country's energy independence by reducing dependence on traditional fuels (Myloslavskyi, 2024).

Undoubtedly, the war has significantly deteriorated the condition of electricity equipment, especially large substations and thermal power plants. It is currently difficult to predict what the state of Ukraine's power system will be like after the war ends, but this state will be the starting point for a phased modernization using smart technologies. After the conflict is over, the country will not only need to rebuild the destroyed infrastructure, but also implement modern solutions that will increase the efficiency and reliability of the power system. This may include the integration of automated control systems, improvement of network infrastructure and development of energy-saving technologies. In addition, the introduction of renewable energy sources, such as solar and wind power plants, will be an important component of Ukraine's energy independence and resilience. Thus, the modernization of the energy system after the war will not only facilitate recovery, but will also provide the basis for the sustainable development of the energy sector in the future.

The most common distributed generation systems based on renewable energy sources include solar panels, wind turbines, small hydropower plants and biofuel plants. While hydropower and biofuel plants are dependent on specific resources, solar and wind power do not have strict location constraints. Hydropower and biofuel plants provide more stable and predictable sources of renewable energy, while wind and solar generation face the problem of unpredictability due to variations in wind flow and solar radiation (Stoliarov, 2024). This makes them dependent on weather conditions, which can complicate the planning and management of energy resources. However, the development of energy-saving technologies and the introduction of forecasting systems can help solve these problems. The use of batteries and other energy storage methods will smooth out fluctuations in energy production, making solar and wind generation more reliable components of the energy system. Thus, the combination of different types of renewable energy sources can provide a more resilient and efficient power system (Abir *et al*., 2021).

Stable voltage in the power grid avoids sudden stops of technological equipment, reduces the number of defective products and improves their quality due to the stability of technological modes. The reliable power supply also has a positive impact on employee productivity and machinery efficiency, as it reduces the likelihood of sudden failures or forced downtime (Rexhaj, 2024). In addition, a stable voltage helps to reduce the cost of maintenance and repair of equipment, as less wear and tear and damage occur. This, in turn, improves the overall financial position of enterprises, allowing them to invest in the development and modernization of production facilities. Improving the reliability of power supply also creates a positive image of the company among customers and partners, as product quality and production stability are critical factors in a competitive environment. Thus, ensuring a stable grid voltage is a key factor in achieving success in any production process.

That is why the issue of studying frequency and power control in the Integrated Power System of Ukraine is becoming particularly important and relevant. This requires taking into account the current operating conditions of the power system, as well as the actual technical condition of the existing equipment. Such studies are necessary to assess compliance with the requirements of the European Network of Transmission System Operators for Electricity, which is a key step in ensuring that Ukraine is connected to the European power system. It is important not only to adapt technologies and procedures, but also to actively implement innovative solutions that will allow Ukraine to integrate into the European energy market. In this context, the development of frequency and power control mechanisms may include the introduction of modern automation systems, improved consumption and production forecasting models, and the expansion of renewable energy sources. All of this will contribute to the creation of a more flexible and sustainable energy system ready for integration into the European energy space and enhancing the country's energy security (Muhammad *et al.*, 2020).

Global trends require large-scale modernization of existing electricity systems to ensure effective integration of green energy. This includes the introduction of high-quality control of energy consumption, improved operational safety, and reduction of the risk of emergencies and their prevention. The current challenges in the energy sector require the use of innovative technologies, such as smart grids, energy storage systems and adaptive demand management (Ali *et al.*, 2022). This will not only optimize production and consumption processes, but also ensure the stability of energy systems during periods of high loads or resource shortages. In addition, the integration of renewable energy sources, such as solar and wind power plants, requires infrastructure upgrades to adapt to their variability. Raising consumer awareness of energy efficiency is also an important aspect, which can have a significant impact on reducing overall energy consumption. All these efforts will contribute not only to the sustainable development of the energy sector, but also to the achievement of global sustainability and climate change goals.

To improve the reliability of renewable energy systems, it is important to combine different types of renewable energy to create hybrid power plants. Such hybrid systems, which combine several energy sources (e.g. solar and wind or solar and hydro), can be effectively used in local power grids. A local power grid can be created on the periphery of the Integrated Power System and include its own hybrid power plant based on renewable energy sources. This grid can be connected to the general grid, acting as a backup and ensuring the stability of the electricity supply in cases where the main grid is under load or has an accident. In addition, hybrid systems in the local power grid can adapt to changes in demand and resources, reducing the risk of supply disruptions. This solution also contributes to the development of energy independence for local communities, allowing them to optimize the use of available resources and reduce energy costs. With the introduction of new technologies and management strategies, such hybrid power plants can become an important element in the transition to a sustainable and efficient energy sector.

Voltage regulation also helps to optimize the use of electricity in production and reduce costs by eliminating cost overruns caused by voltage surges. It is an important tool for increasing the efficiency of industrial enterprises. Ensuring a stable voltage level not only helps to reduce energy costs, but also helps to reduce the risk of damage to electrical equipment, which can lead to costly repairs and production downtime. As a result, businesses can achieve greater productivity and reliability in their operations. In addition, voltage regulation allows for more precise process control, which in turn improves product quality. This is especially important in a competitive market, where every percentage point of savings and quality improvement can have a significant impact on financial results. Consequently, the implementation of efficient voltage control systems is becoming critical to succeeding in today's manufacturing environment (Ismayilzada *et al.*, 2024).

According to the structure of a smart electricity system, there are several key areas of implementation of this concept (Fig. 1). In Smart Grid systems, electricity generation has its own peculiarities: instead of the traditional centralized scheme (top-down power flow), there is a transition to distributed generation (bottom-up power flow). This means that numerous energy sources, such as solar, wind, biogas, hydroelectric power plants and others, are being connected to the grid at the voltage level of 0.4-35 kV, creating the so-called Micro Grid or distributed generation systems. These systems have their advantages and disadvantages. The main advantages include greater flexibility and the possibility of local energy generation. However, there are also significant challenges, including the difficulty of balancing the power system due to uneven consumption and generation, the problem of reactive power flows, and the occurrence of higher harmonics. Another important issue is the accumulation of excess electricity, which requires the construction of various types of storage facilities to make efficient use of resources and reduce energy losses.

Transmission and distribution of electricity in smart grids is carried out using automated systems that allow monitoring and controlling energy distribution in real time. This enables operators to respond quickly to changes in supply and demand. In addition, Smart Grid technologies automatically detect power failures and can restore power supply, which significantly reduces the time of outages and increases the reliability of power supply. Such systems also enable consumers to generate their own energy and connect to distribution networks, which reduces the load on centralized energy sources. However, the efficient transmission and distribution of electricity requires the modernization of key grid components, including power equipment, communication and information devices, as well as automated control and metering systems.

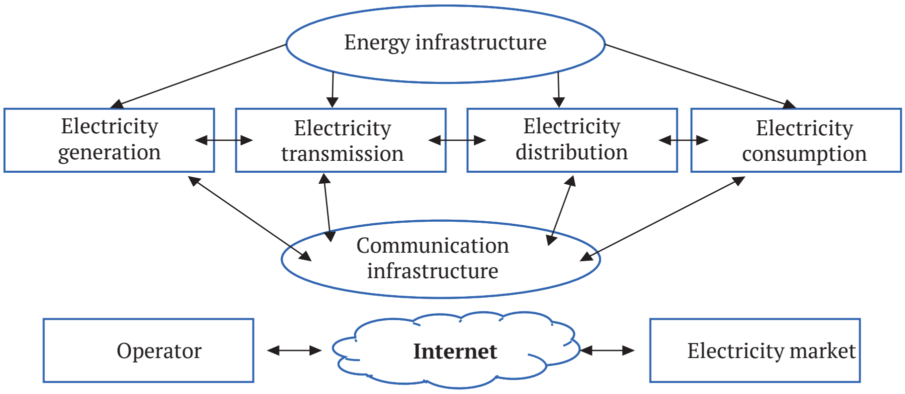

Figure 1. Interaction of elements of a smart electricity system
Source: compiled by the authors based on C. Kaur *et al*. (2024)

Therefore, the right approach to creating a hybrid local power system using storage capacities such as batteries, hydrogen systems, and others will allow us to fully meet the needs of consumers. With the energy balance approaching zero at the point of power supply, this will help reduce the load on the general grid. Thus, consumers will receive reliable and high-quality electricity, and transmission losses in the Integrated Power System will be reduced due to distributed generation.

The modern electricity system is a complex, multi-parameter and dynamic system with high rigidity. Adequate modelling of the processes occurring in the equipment and in the system as a whole is a challenging task. Most studies focus on modelling the power equipment of the electric power system, while relay protection devices are usually modelled in a simplified way. However, the nature of transients during various disturbances in a real power system often depends on the response time of relay protection and emergency automation devices. This also applies to electromechanical transients, the duration, and characteristics of which determine the further operation and stability of the power system.

The introduction of smart grids will contribute to the creation of the power grid as an intelligent system for the transmission, distribution, and supply of electricity from producers to consumers. The grid will be integrated with communication and information technologies, which will improve the efficiency of the power system and provide better service to its users. The schedule of the required voltage at the grid control points is usually drawn up in advance for a three-month period or the relevant season. However, when developing it, it is impossible to accurately predict all the modes that will arise during the programme, given possible fluctuations in consumption and production levels, as well as changes in the grid layout. In addition, weather conditions cannot be fully taken into account when scheduling. For example, this is important for accurate modelling of power losses due to corona discharge on overhead lines when optimizing voltage and reactive power modes.

Operational control devices (e.g., Siemens) are important elements in the automation of power systems during blackouts. They contribute to the efficient management of energy resources and increase grid reliability. Due to their flexibility and the ability to integrate with modern technologies such as the Internet of Things, these devices allow for adaptation to changes in production processes and technological conditions. This ensures a quick response to market changes and increases the efficiency of energy system management.

Any energy grid in the world has a certain drawback, which is the possibility of rapid spread of abnormalities in one part of the system, which can lead to so-called systemic accidents, cutting off power to consumers over large areas. Experience has shown that the most effective way to prevent such accidents is to improve power system management. This management is usually divided into two main classes: operational dispatch and automatic. Since accidents in power systems develop very quickly, the human factor in dispatch control often does not have time to cope with the tasks that arise, so automatic control plays an important role, complementing the actions of the operator.

The voltage regulating device is mounted on transformers with a voltage of 35 kV and above, located on the neutral of the high-voltage winding. This results in the number of turns in the high-voltage winding exceeding the number of turns in the low-voltage winding. When switching, a lower current is connected than on the low voltage side. Connecting voltage regulators to the grounded neutral at high voltage significantly reduces the insulation requirements of the regulator, providing smoother regulation. A simplified switching diagram for a two-tap transformer branch is shown in Figure 2.

On the high voltage side of the transformer, there are regulated, and unregulated windings connected in series. Both windings are in the same magnetic circuit, which also contains the low voltage winding. The regulated winding has a control range of ±9% to ±12% or ±16% of the nominal voltage *U*nom, with a control step of 1.5% or 1.78%, which can cover 12, 16 or 18 steps. The tap changer consists of two switches, two contactors and a current-limiting reactor. The current in the high voltage winding passes through the reactor in opposite directions, which ensures low magnetic flux and low reactor resistance.

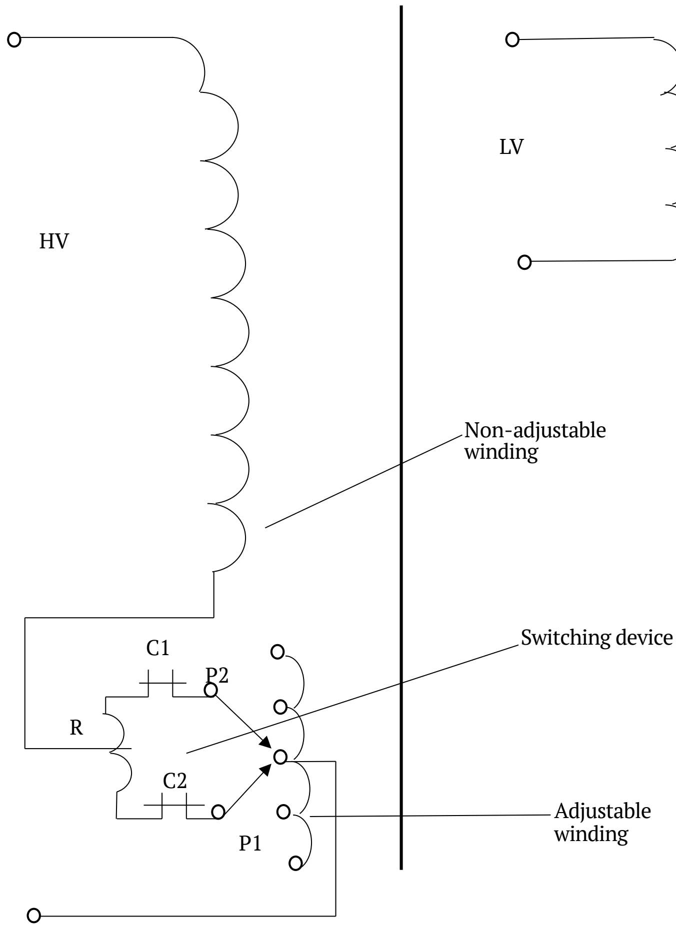

Figure 2. Voltage control circuit for transformers with two windings
Note: HV – high voltage, LV – low voltage, C1 and C2 – commutators, R – regulating device, P1 – primary winding, P2 – secondary winding
Source: compiled by the authors based on G. Liobikienė *et al*. (2024)

System automation (power system automation) has several specific features that distinguish it from general industrial automation. The main feature is that system automation devices do not operate autonomously. Although they may be structurally autonomous, their operation is closely linked through processes in the power system, and they affect both the power system as a whole and each other's operation. Taking into account the state of the electricity sector and current global trends, Ukraine's Energy Strategy for the period up to 2050 sets several key goals. These include achieving the maximum level of climate neutrality, renewal, and modernization of energy infrastructure, increasing the efficiency of resource use in the energy sector, comprehensive integration with the European Union markets and ensuring the efficient functioning of domestic markets. It also focuses on the development of alternative energy sources, new products and innovative solutions in this area. In March 2024, as a result of missile attacks by the Russian army, thermal power facilities and hydroelectric power plants, which played an important role in maintaining the balance of the power system during peak loads, were severely damaged. On 31 March, Ukraine's power system recorded a surplus of capacity due to the active operation of solar power plants, which avoided a power shortage, according to the Ministry of Energy (Liobikienė *et al*., 2024). Thus, the development of decentralized renewable energy is becoming an important area for minimizing blackout risks in Ukraine that may arise as a result of new attacks on energy infrastructure by the Russian military.

DISCUSSION

The transition of power systems to the Smart Grid concept requires solving several key tasks, including those related to improving the power flow management system in electricity networks. Managing power flows is critical to ensuring stable and efficient operation of the power system, especially given the growing number of renewable energy sources and changes in the demand structure. Automated power flow management systems allow Smart Grids to control the transmission of electricity between different parts of the grid in real-time. This allows for prompt response to changes in load, redistribution of energy flows, minimization of losses and avoidance of overloading of individual lines.

The results of the study confirmed that the main mechanism underlying the advanced power flow management system is to ensure a balance between electricity generation and consumption. This is achieved by automatically regulating power flows in real-time, considering the dynamics of demand and changes in generation, including from renewable sources. These results indicate that within the Smart Grid concept, balancing is carried out using intelligent forecasting algorithms that take into account the variability of consumption and generation, especially in the context of renewable energy sources such as solar and wind power plants.

Similar conclusions were reached by T. Kurbatova *et al.* (2024) and J.S. Ríos *et al*. (2024), who provided in their studies an overview of the most common methods of power flow management. Their analysis considered both active powers consumed by users and reactive power, which plays a key role in maintaining a stable grid voltage. These methods are key in the Smart Grid, where advanced optimization solutions are used to ensure a balance between active and reactive power, which helps prevent overloads and improve grid stability. The authors discussed methods where one of the key challenges of Smart Grid is the integration of various energy sources, including distributed generation such as solar panels and wind turbines, into the overall power system. This allows for greater flexibility and resilience of the grid, promoting more efficient use of renewable energy sources and reducing dependence on traditional generators.

The study found that the integration of renewable energy sources creates additional challenges for managing power flows. This is due to the fact that the generation from such sources is unstable, and the distribution of energy needs to be constantly adjusted.

The authors F. Khan & A. Rapposelli (2024), and N. Naseri *et al.* (2024), in their studies, emphasize that Smart Grid provides automated control of energy flows with minimal energy losses. The system uses modern algorithms and technologies for flexible energy distribution, which allows for an effective response to changing demand and variations in generation, including from renewable sources. Such a comprehensive Smart Grid provides dynamic load management in different parts of the power system. Their results point to the lack of effective demand management in power systems. This can be addressed by Demand Response technologies, which allow consumers to adjust their electricity consumption in real-time according to the current load on the grid.

In the context of resilience research, this approach helps prevent grid overloads and maintains the stability of electricity supply even during peak periods. Through the use of appropriate devices, Smart Grid can create microgrids that can function both independently and in integration with the main grid. In real life, this reduces the load on the main grid and improves its resilience to emergencies. Monitoring the management of energy flows in microgrids ensures efficient load regulation and stability of operation even in critical situations. With improved monitoring and management of energy flows, Smart Grid can reduce energy losses during transmission. This study highlights the importance of power system analysis, which becomes particularly important when distances are long, or the network is congested. The analysis of these parameters contributes to a deeper understanding of the mechanisms that influence effective management, which significantly improves the overall energy efficiency of the system.

Research in this area was also conducted by P. Maneejuk *et al.* (2024), S. Abdelkader *et al.* (2024) and M.A. Sayed *et al.* (2024). They created a new mechanism that provides high control accuracy, while improving the power flow control system within the Smart Grid includes comprehensive cybersecurity measures. This is crucial to protect the infrastructure from potential cyberattacks that could cause serious disruptions to the power grid and to guarantee a stable and reliable energy supply in the face of growing threats. Their work has highlighted the need for integration, as these systems are digitally based and interact with different elements of the grid via the Internet. Therefore, it is important to ensure reliable protection against cyber-attacks that could adversely affect the management of power flows and the stability of the power system. This approach not only ensures effective hardening of the power system, but also allows Smart Grid to not only improve the reliability and resilience of power grids, but also to provide more efficient management in the face of variable demand and the integration of renewable energy sources. It also helps to reduce energy costs and improve overall energy efficiency, which in turn helps to ensure the stability and cost-effectiveness of the power system. Ukraine's distribution grids, which operate at voltages ranging from 0.4 to 35 kV, play a critical role in providing electricity at all levels, from households to industrial facilities (Serdyuk *et al.*, 2024).

Low-voltage networks (0.4 kV) supply electricity directly to end users, including households and small businesses. The electricity supply process includes transformer substations that reduce the voltage to a level suitable for consumption. Medium-voltage networks (10-35 kV) in this study are responsible for supplying electricity to large areas and industrial facilities. They are responsible for transporting electricity from transformer substations to low-voltage distribution systems, ensuring efficient distribution of electricity at the local level. This allows energy to be delivered to end-users such as households, commercial and industrial facilities, and maintains the stability and reliability of the electricity supply.

The study by F. Alasali *et al.* (2024) and A. Bebboukha *et al.* (2024), like the present study, focus on substations that provide further voltage reduction. The authors note that distribution networks guarantee a reliable and stable electricity supply for all consumer groups. Observations have shown that these networks are critical for the transmission of electricity from large generators to end users.

The results showed that these networks distribute the electrical power received from large transformer substations to smaller areas according to the needs of consumers.

Distribution networks equipped with monitoring and control systems to ensure uninterrupted power supply and rapid response to emergencies were analysed. Consequently, many distribution networks in Ukraine are in need of modernization due to old equipment that can impair their reliability and efficiency. This study notes that the increasing number of renewable energy sources, such as solar and wind power plants, requires the adaptation of distribution networks to integrate new sources and manage their variable generation. The present study notes that with the development of digital technologies for monitoring and controlling power grids, there is a growing need to strengthen cybersecurity to protect grids from potential cyberattacks. One of the main ways to improve energy efficiency is to modernize existing systems and introduce the latest power management technologies. This involves the use of modern solutions to reduce energy losses, optimize power distribution and improve the overall efficiency of the energy system.

V.-L. Trinh & C.-K. Chung (2024) reached similar conclusions using a different method. They investigated the impact of introducing Smart Grid technologies that help optimize energy flow management, integrate renewable energy sources, and provide increased resilience and efficiency to distribution networks through various mechanisms. It found that the creation of microgrids that can operate both autonomously and in integration with the main grid helps to improve reliability and reduce the load on central systems. Strategies and recommendations have been developed that emphasize the critical importance of distribution networks for the stability of the national energy system. They point to the need for continuous improvement and innovation to ensure efficient and reliable electricity supply.

Overall, the results of the study make a significant contribution to the understanding of transformers and load-following autotransformers, which are key elements of power grids. They play a key role in ensuring the stability and efficiency of the system, allowing voltage regulation without the need to disconnect the load. To ensure reliable operation of transformers and autotransformers, it is necessary to implement modern diagnostic and monitoring systems. The study showed that modern diagnostic systems allow for real-time monitoring of equipment conditions, including temperature conditions, insulation wear, oil quality, and the state of the tap changer (TC) contacts.

Measures such as the use of these technologies help to detect potential malfunctions at an early stage and prevent accidents, which reduces operational risks. In addition, it helps to improve overall system reliability and extend equipment life. It has also been found that to maximize transformer performance, it is necessary to create conditions that ensure optimal operation. This includes maintaining proper temperature conditions, regular maintenance checks, and the use of advanced load management techniques to improve the efficiency and reliability of the equipment.

CONCLUSIONS

It has been found that poor regulation of disruptions in the normal functioning of power grids leads to a number of negative social and economic phenomena. These include not only a decrease in the efficiency of energy supply, but also an increase in the cost of restoring systems, which in turn can lead to higher tariffs for consumers.

The study also confirmed that compliance with standards is critical, in particular, in the context of regulating the primary bus voltage at power plants and substations that use regulated reactive power compensation. Currently, this practice remains less widespread than it could be, which can have a negative impact on the overall stability and reliability of the power system. The lack of proper control over these parameters can lead to voltage fluctuations, increased energy losses, and increased risks of emergencies.

The study analysed and examined the impact of the ageing effect on various components of electric power systems (EPS), including primary motors, generators, transformers, power lines, various power consumers and other main and auxiliary equipment. It is the study of how these elements are interconnected within the processes of electricity generation, transmission, distribution, and consumption. Research in this area is focused on optimizing modelling processes and developing solutions that will help overcome these negative phenomena, in particular through the introduction of smart grids. To date, regular monitoring and maintenance has shown that interruptions in power supply led to underproduction, lower quality, defective products, cost overruns or underutilization of resources. It can also cause equipment to break down in both industrial plants and residential buildings, causing significant losses to the economy. Regular training in modelling optimal switching schemes for power grids has played an important role in improving the efficiency of blackout management. This not only provides a more cost-effective approach to managing electricity supply, but also makes modelling methods more promising than traditional approaches.

Further research in this area could include the development and testing of new methods and technologies for modelling optimal switching schemes for Ukraine's power grids during a blackout in a single city. This includes improving management techniques that ensure reliability and efficiency in blackout situations, as well as integrating new solutions that minimize risks. An analysis of the impact of this method shows that it requires relatively low costs, which is especially important in the context of growing electricity consumption.

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CONFLICT OF INTEREST

None.

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Моделювання оптимальної схеми перемикання електромереж України під час блекауту в одному місті/регіоні

Анотація. Мета дослідження полягала у розробці ефективних алгоритмів і стратегій для мінімізації негативних наслідків аварійних відключень електроенергії. Було розроблено методологію, яка визначає кроки та процеси для ефективного моделювання та відбору оптимальних схем перемикання електромереж, що здатні забезпечити стабільність енергопостачання та підвищити стійкість мережі під час блекауту в окремому місті або регіоні. У результаті дослідження було розроблено й удосконалено схему перемикання електромереж для використання в умовах воєнних та інших кризових ситуацій. Проведено вивчення можливих сценаріїв відключення електроенергії, що дозволило врахувати різні варіанти реагування та забезпечити максимальну ефективність і надійність енергопостачання під час аварійних ситуацій. На основі даних, з урахуванням додаткових аспектів безпеки та надійності мережі, були визначені оптимальні маршрути передачі електроенергії, розташування резервних джерел живлення. Крім того, було проведено оцінку ризиків для забезпечення стабільної роботи системи під час кризових ситуацій, що дозволило підвищити її стійкість до можливих збоїв. Аналіз існуючих методів, таких як ручне перемикання мереж, використання автоматизованих систем та залучення резервних джерел живлення, дозволив визначити переваги та недоліки кожного підходу для забезпечення стабільного електропостачання під час блекауту в одному місті або регіоні. У результаті було встановлено, що завдяки оптимізації схеми перемикання мережі можна мінімізувати шкоду від відключень електроенергії. Також були визначені переваги та недоліки різних підходів, і результати дослідження підтвердили, що оптимальна схема перемикання електромережі значно зменшує тривалість відключення електроенергії

Ключові слова: енергетична стійкість; аварійне управління; резервні джерела живлення; аналіз відключень; енергетичні кризи; управління навантаженням

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Experimental study of heat exchangers and mixing machines operation optimisation methods

Abstract. The study aimed to optimise the operation of heat exchangers and mixing machines to improve the efficiency of production processes. An experimental approach with models that describe the processes of heat transfer, hydraulic resistance and mixture homogeneity was used to determine the optimal equipment parameters. The study showed that optimisation of the operation of heat exchangers can lead to a significant increase in energy efficiency and a reduction in operating costs. The best results were achieved at a coolant temperature of 90°C and a pressure of 5 bar, which resulted in a maximum heat transfer of 350,000 W. The study determined that reducing the hydraulic resistance to the optimum level can reduce energy costs for pumping coolant by 15%. The study also showed that to achieve maximum homogeneity of the mixture in mixing machines, the optimal rotation speed is 400 rpm. This resulted in a mixture homogeneity index of 16. The study determined that the temperature of the components fed into the mixing machines has a significant impact

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on the final product quality. For example, the optimum temperature for certain components had reduced mixing time by 10%, which had contributed to an increase in overall productivity. The integration of automatic control systems, such as the automatic control system, allowed for real-time monitoring and adjustment of equipment parameters, which further increased the efficiency of production processes. In addition, the study determined that comprehensive optimisation of the parameters of the devices' operation allows for an increase in the duration of their life cycle, reducing the frequency of maintenance by 20%. Optimisation of the operation of heat exchangers and mixing machines significantly increases production efficiency and the quality of final products, contributing to cost reduction and increasing equipment reliability

Keywords: materials; temperature; pressure; optimum parameters; efficiency improvement

INTRODUCTION

In modern environment, improving the efficiency of production processes is critical to the competitiveness of enterprises. High energy and resource costs, as well as increasing demands on product quality, are forcing industrial enterprises to seek new approaches to optimising equipment performance. Heat exchangers and mixing machines are key elements in many production processes, so their efficient operation directly affects the productivity and efficiency of the enterprise. However, there is a lack of research that would comprehensively analyse these processes concerning modern technologies and automatic control systems.

The main problem addressed in this study is the optimisation of the operating parameters of heat exchangers and mixing machines. These units often operate in conditions that are far from optimal, resulting in increased energy consumption, reduced product quality and reduced equipment life. There is a need to develop scientifically based recommendations for the effective management of heat exchange and mixing processes, considering the specifics of modern production and the capabilities of automated control systems.

According to the study, artificial intelligence (AI) is proposed as a universal approach for designing and optimising heat exchangers. J. Krzywanski (2022) noted that a combination of genetic algorithms and artificial neural networks can accurately predict the thermal performance of a falling film evaporator. C. Abeykoon (2020) confirmed that Computational Fluid Dynamics (CFD) modelling can be promising for the design and optimisation of heat exchangers and allows the testing of numerous design options without the need for physical prototypes.

M.H. Mohammadi *et al*. (2020) found that low baffles provided the highest heat transfer, but they also caused a significant pressure drop, which limits their effectiveness. A porosity of 0.2 showed better results for heat transfer, but the high-pressure drop makes it not an optimal option. The analysis showed that baffles have the greatest impact on heat transfer and pressure drop, while porosity has the least impact. Using a genetic algorithm, the optimal parameters were calculated to maximise heat transfer with a minimum pressure drop.

D. Gürses *et al*. (2023) presented the Multi-Strategy Boosted Prairie Dog Optimisation Algorithm for optimising three types of heat exchangers (shell-and-tube, fin-and-tube, and plate-and-fin) with a focus on minimising installation and maintenance costs. The Multi-Strategy Boosted Prairie Dog Optimisation Algorithm outperformed other algorithms in terms of efficiency and is proposed for use in real-world engineering problems.

Researches C. Elsido *et al*. (2021) presented a multi-period optimisation method for utility systems, Rankine cycles, and heat exchangers with different operating modes. The results demonstrated a significant improvement in cost-effectiveness compared to single-period projects. A.H. Pordanjani *et al*. (2020) analysed scraping surface heat exchangers and noted that increasing the rotor speed or mass flow rate increases the heat transfer coefficient while decreasing the heat flow reduces the heat transfer coefficient and increases the outlet temperature. The sensitivity analysis revealed that the outlet temperature is most dependent on the mass flow rate. Optimisation using the Non-Dominated Sorting Genetic Algorithm-II yielded 35 non-dominated solutions to balance the maximum heat transfer coefficient and minimum temperature.

Scientists J.M. Zamora *et al*. (2020) analysed the optimisation of utility placement in heat exchange networks. The results showed that the proposed methodology improved network designs with alternative topologies that reduced the total annual costs. Four examples have confirmed the effectiveness of this approach. M. Ghalandari *et al*. (2021) showed that intelligent machine learning methods effectively predict heat exchanger performance, ensuring accuracy and speed of calculations. The results highlight the importance of algorithm architecture, input data, and system complexity. Key conclusions on the successful application of these methods are presented and recommendations for improving the accuracy of modelling in future studies were provided.

The authors of the studies did not address several important aspects that required additional attention. D. Gürses *et al*. (2023) and C. Elsido *et al*. (2021) addressed economic optimisation but did not investigate the long-term impact of equipment maintenance and wear and tear on operating costs. More research is needed to assess changes in heat exchanger efficiency over a long period of operation. Environmental aspects were understudied in studies such as C. Abeykoon (2020). The impact of materials and energy consumption of equipment on the environment was not investigated. Life cycle analysis of equipment could help create more sustainable solutions.

M.H. Mohammadi *et al*. (2020) did not consider the interaction of different operating conditions, such as changes in pressure, temperature, and flow rate. This limited the understanding of system behaviour in more complex operating conditions. C. Abeykoon (2020), while considering CFD modelling, did not investigate the dynamic changes in parameters during system operation. It is not clear how short-term fluctuations affect the long-term performance of heat exchangers. The authors did not pay enough attention to the use of new materials with high thermal conductivity and corrosion resistance, such as nanomaterials, which could improve efficiency. M. Ghalandari *et al*. (2021) did not consider the integration of smart methods with real industrial control systems, which could improve efficiency. Most studies, such as the one by J.M. Zamora *et al*. (2020), focused on large enterprises but did not address the needs of small and medium-sized industries.

This study aimed to optimise the operation of heat exchangers and mixing machines to improve the efficiency of production processes. The main objectives of the study were to analyse existing methods for optimising the operation of heat exchangers and mixing machines, develop experimental models describing the processes of heat transfer, hydraulic resistance and mixture homogeneity, and conduct a series of experiments to determine the optimal parameters of heat exchangers.

MATERIALS AND METHODS

At the first stage of the study, existing methods and approaches to optimising the operation of heat exchangers and mixing machines were collected and analysed. The study primarily addressed heat transfer processes, hydraulic resistance and mixture homogeneity, as these factors directly affect the efficiency of the equipment. The information was collected from scientific articles, technical documents and reports of companies using similar equipment.

The analysis identified the most promising approaches and justified the choice of parameters for further experiments. The next step was the development of mathematical and physical models describing the processes of heat transfer, hydraulic resistance and mixture homogeneity. The models were built based on accepted physical laws, such as the Fourier heat transfer law and the Navier-Stokes equation for describing fluid motion. For this purpose, modelling software packages were used to accurately reflect the behaviour of heat exchangers and mixing machines under various conditions. Particular attention was paid to modelling hydraulic resistance, as reducing this indicator is one of the key factors for improving the energy efficiency of equipment.

The study included a series of experiments. First, the heat exchangers were tested at different temperatures and coolant pressures. The main goal was to determine the optimal parameters at which maximum heat transfer is achieved with minimal energy consumption. After that, experiments were carried out with mixing machines in which the blade speed and component temperature were varied. Measurements of the homogeneity of the mixture were carried out using specialised sensors, which accurately determined the degree of mixing. Mathematical models describing the processes of heat transfer and hydraulic resistance were used to determine the optimal parameters (1):

$$Q = k \times A \times \Delta T, \tag{1}$$

where Q – amount of heat transferred; k – heat transfer coefficient; A – heat transfer surface area; ΔT – temperature difference between heat transfer fluids.

The formula for determining the homogeneity score of a mixture (2):

$$U = k \times RPM^{0.5}, \tag{2}$$

where U – homogeneity index; $k = 0.8$, and rpm – rotations per minute. Speeds from 100 to 400 rpm were tested.

The formula for determining the homogeneity of a mixture (3):

$$U = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{c_i}{c_{aug}}\right) \times 100\%, \tag{3}$$

where c_i – concentration of components in the sample; c_{aug} – average concentration; n – number of samples.

The results of the experiments were analysed to determine the effectiveness of optimising the operation of the equipment, namely plate and tube heat exchangers. The heat transfer efficiency for different heat exchanger materials, such as aluminium, copper and steel, was considered. Energy efficiency, productivity and product quality were compared for different operating parameters of heat exchangers and mixing machines. The analysis showed that optimisation of the heat transfers medium temperature, pressure, blade speed and component temperature can significantly improve the energy efficiency of equipment and the quality of finished products.

RESULTS

Optimisation of the performance of heat exchangers and mixing machines is a key task in industrial processes, as it can increase efficiency, reduce costs and ensure consistent product quality (Rao *et al.*, 2020). Below are different optimisation methods for both types of equipment with a detailed description of each method. Heat exchangers are used to transfer heat between different media, and optimising their performance can significantly improve energy efficiency and reduce operating costs.

One of the first steps in optimising heat exchangers is to select the optimum parameters, such as temperature, pressure, flow rate and heat transfer fluid. For this purpose, modelling and calculations are usually used to determine the optimal conditions under which the maximum heat transfer efficiency will be achieved (Saeed *et al.*, 2022). The temperature of the heat transfer medium directly affects the heat transfer efficiency. An increase in temperature increases the temperature difference between the coolant and the cooled medium, which increases the heat transfer coefficient. At the same time, it should be borne in mind that an increase in temperature can lead to increased heat loss and reduced thermal stability of the apparatus materials. Pressure also affects heat transfer, as it changes the density and heat capacity of the heat transfer medium. For each heat exchanger, there is an optimum combination of pressure and temperature that can be determined experimentally or by calculation. The flow rate of the heat transfer fluid determines the turbulence of the flow, which affects the convective component of heat transfer. Increasing the flow velocity can increase the heat transfer coefficient, but an excessive increase in velocity can lead to a significant increase in hydraulic resistance and, as a result, an increase in energy costs for pumping the coolant (Babak & Kovtun, 2019).

Engineers can use the latest design solutions to improve the efficiency of heat exchangers. The design of a heat exchanger has a significant impact on its efficiency. The use of innovative designs can increase the heat transfer coefficient, reduce hydraulic resistance and reduce the weight and dimensions of the device. The most common designs are tubular, plate and spiral heat exchangers. Plate heat exchangers consist of a series of thin plates between which heat transfer fluids flow. Each plate creates a large heat transfer area with a small footprint, which ensures a high heat transfer coefficient (Spivak *et al.*, 2024). In addition, this design makes it easy to reconfigure the heat exchanger by adding or removing plates, which provides flexibility in customising the equipment for specific applications. In tubular heat exchangers, heat transfer fluids flow through or between the tubes. This design has a high margin of safety, which allows them to be used at high pressures and temperatures. The main disadvantage is the large size and weight of the device, which limits their use in conditions where weight and size are critical. Spiral heat exchangers are used in conditions of high hydraulic loads. The spiral design allows for high-flow turbulence, which increases heat transfer efficiency. In addition, this design ensures uniform distribution of the heat transfer medium over the heat transfer surface (Zamora *et al.*, 2020).

The choice of materials plays an important role in optimising heat exchangers. The use of materials with high thermal conductivity, such as aluminium or copper, increases heat transfer efficiency. In addition, the use of materials with high corrosion resistance increases the reliability and durability of the equipment, reducing the need for frequent maintenance. The use of innovative materials in heat exchangers can improve their efficiency, reduce weight and size, and increase service life (Orumbayev *et al.*, 2021). Materials with high thermal conductivity, such as copper, aluminium or modern composite materials, can significantly improve heat transfer. Copper has high thermal conductivity and corrosion resistance, making it an ideal material for heat exchangers operating in high temperatures and corrosive environments (Wang *et al.*, 2021). Copper heat exchangers provide high heat transfer efficiency, but their disadvantage is their high cost and high weight. Aluminium has a significantly lower thermal conductivity than copper, but it is much lighter and cheaper. Aluminium heat exchangers are used where weight and cost are critical. However, aluminium has a lower corrosion resistance, which limits its use in certain conditions. Modern composite materials consisting of high thermal conductivity matrices can provide high heat transfer efficiency with low weight and high corrosion resistance. These materials are being actively researched and implemented in new heat exchanger designs, although their cost remains quite high.

Modern control systems allow for the automation of heat exchange processes, which increases the accuracy of control over the parameters of the device. Automated systems can instantly respond to changes in operating conditions, ensuring that optimal parameters are maintained at all times and reducing the risk of emergencies (Kola *et al.*, 2021).

Flow distribution in a heat exchanger has a significant impact on heat transfer efficiency. Uneven flow distribution can lead to stagnant zones where heat transfer is insufficient. Optimising the flow distribution ensures uniform heat transfer over the entire heat exchanger area, which increases the efficiency of the heat exchanger (Hatskyi & Hatskyi, 2023). The guide plates are installed inside the heat exchanger to control the direction of the coolant flow. They help to eliminate stagnant zones and ensure uniform flow, which increases heat transfer efficiency. Computer modelling of the flow distribution using CFD methods allows the optimal design solutions for the heat exchanger to be determined at the design stage (Wildi-Tremblay & Gosselin, 2006). This helps to avoid mistakes that can reduce the efficiency of the unit.

Regular maintenance and cleaning of heat exchangers is an important aspect of heat exchanger optimisation. Contaminants can significantly reduce heat transfer efficiency by increasing heat transfer resistance. Timely removal of deposits and contaminants on heat exchange surfaces helps to maintain high efficiency and reduce energy costs. Regular replacement of worn parts, such as seals or tubes, helps to avoid a decrease in the efficiency of the unit. Mixing machines are used to homogeneously mix various components in production processes (Aresti *et al.*, 2020). Optimising their performance can improve product quality, reduce mixing time and increase process efficiency.

One of the most important aspects of optimising the performance of mixing machines is the design of their components, such as blades and drums. Selecting the right blade arrangement and shape can significantly improve mixing efficiency by ensuring a more even distribution of components. The use of special blade shapes, such as helical or spiral, can increase mixing efficiency and reduce the time required to achieve homogeneity of the mixture (Dong *et al.*, 2020). Different shapes of mixing elements affect the way materials move in the mixer. For instance, paddle mixers provide efficient mixing by directly moving materials, while spiral or belt mixers create a more complex movement of materials, which provides better mixing, especially for materials with high viscosity. The material of the mixing element should be selected following the characteristics of the material to be mixed. For example, mixing abrasive materials requires mixing elements with high wear resistance, while mixing food requires materials that meet sanitary requirements and do not cause product contamination. The size of the mixing element also affects the mixing process. Too large elements can create stagnant zones where the material is not mixed properly, while too small elements may not provide enough force to mix heavy or viscous materials (Biçer *et al.*, 2020).

The rotational speed of the mixing elements is a critical parameter that affects the mixing quality (Lerou *et al.*, 2005). Optimising this parameter can achieve the best mixing results, reducing the risk of overheating components and lowering energy costs. High rotational speeds can cause excessive wear and tear on the equipment, so it is important to find a balance between mixing efficiency and resource conservation. Increasing the rotational speed of the mixing element increases the turbulence of the material flow, which contributes to a more even distribution of the components in the mixture (Havrylenko *et al.*, 2021). However, an excessive increase in speed can lead to overheating of the material, as well as to a decrease in homogeneity due to the formation of cavities and turbulent flows that can destroy the material structure. Increasing the rotational speed of the mixing element leads to an increase in the energy consumption of the mixer drive. Therefore, it is important to find a compromise between the mixing intensity and energy consumption, which can be done by experimental speed selection (Jamil *et al.*, 2020). Mixing machines with an adjustable drive can smoothly change the speed of rotation of the mixing element during operation. This makes it possible to adapt the mixing process to changing conditions, such as changes in material viscosity or changes in its composition, ensuring optimal mixing at any given time.

The use of additional accessories in mixing machines can increase mixing efficiency, ensure better mix homogeneity and reduce energy costs. Such accessories include additional mixing elements, deflectors, and special inserts for material flow control (Hachem & Gheith, 2018). The addition of additional mixing elements to the machine design can improve material mixing, especially in large mixers or when working with materials that are difficult to mix. Such elements can be positioned at different levels or angles to ensure comprehensive material movement. Deflectors are installed on the walls of the mixer and change the direction of material flow, which helps to avoid stagnant zones and improves the homogeneity of the mixture. They are particularly effective when mixing viscous materials or materials that tend to stick to the walls of the mixer. Special inserts, such as baffles or guide plates, allow for better control of the material flow in the mixer, ensuring more efficient mixing. They can be customised for specific tasks, for example, to mix materials with different properties or to avoid segregation of the mixture components (Zhang *et al.*, 2019).

The introduction of sensor systems for monitoring mixing parameters allows for real-time monitoring of the quality of the mixture and adjustments to the machine. Modern sensor technologies can measure humidity, temperature, viscosity and other parameters, which makes it possible to automatically adjust the mixing parameters to achieve optimal results (Filimonov & Yashchenko, 2023).

Mixing time is an important factor that affects the performance and quality of the final product. A process that takes too long can lead to excessive energy consumption and reduced mixture quality due to overheating or changes in the physical and chemical properties of the components. Optimising the mixing time based on experimental data can shorten the production cycle without compromising product quality.

Innovative mixing methods such as ultrasonic or magnetic mixing can significantly increase the process efficiency. Ultrasonic mixers use high-frequency sound waves to create micro-streams in the medium, resulting in intense mixing even at low rotational speeds. Magnetic mixers, in turn, avoid mechanical contact between components and mixing elements, which reduces equipment wear and tear (Liang *et al.*, 2022).

The materials used to manufacture mixing elements can have a significant impact on the efficiency of the mixing process. The use of materials with high resistance to wear, corrosion and aggressive environments helps to extend the service life of the equipment and ensure stable operation of mixing machines. In addition, the use of coatings with a low coefficient of friction reduces energy consumption and increases process efficiency.

The optimisation of heat exchangers and mixing machines has its characteristics, but general principles, such as the selection of optimal parameters, automation, and the use of innovative materials and technologies, are common to both types of equipment (Bahiraei *et al.*, 2021). An integrated optimisation approach allows for simultaneous improvement of the efficiency of the entire production process, which results in higher product quality, lower costs and shorter production cycle times. Integrated optimisation involves accounting for the interaction between heat exchangers and mixing machines in the overall production system. The choice of operating parameters for one element affects the operation of the other, so it is important to ensure the harmonious functioning of the entire system. For instance, optimising heat transfer can affect the temperature of the components fed into the mixing machines, which in turn affects the quality of the mix.

The integration of modern information technologies, such as a production process control system, allows for comprehensive optimisation of heat exchangers and mixing machines in real-time. This ensures a quick response to changes in the production process and allows for automatic adjustment of operating parameters to achieve maximum efficiency (Zhou *et al.*, 2022). Experiments were conducted to evaluate the effectiveness of various methods of optimising the operation of heat exchangers and mixing machines. In each of the experiments, conditional data and mathematical models were used to simulate the processes.

The first experiment aimed to determine the optimum temperature and pressure to maximise heat transfer efficiency. The temperature of the heat transfer medium was varied from 50°C to 90°C, and the pressure was from 1 to 5 Bar (Table 1). Formula (1) was used to calculate the heat transfer. The results of the experiment showed that the maximum heat transfer was achieved at a temperature of 90°C and a pressure of 5 Bar, which corresponds to a value of 350,000 W.

Table 1. Effect of temperature and pressure on heat transfer efficiency

Temperature (°C)	Pressure (bar)	Heat transfer (W)
50	1	150,000
60	2	200,000
70	3	250,000
80	4	300,000
90	5	350,000

Source: compiled by the authors

The second experiment was aimed at comparing the efficiency of different heat exchanger designs, such as plate and tube. The heat transfer formula (1) was used for the assessment. For the plate heat exchanger, the coefficient *k* multiplied by 1.2 was used, while for the tube heat exchanger, it was multiplied by 1. A temperature of 70°C and a pressure of 3 Bar was used. The results showed that the plate heat exchanger had a heat transfer of 300,000 W, which is 20% higher than the tube heat exchanger, which reached 250,000 W (Table 2).

Table 2. Comparison of the efficiency of plate and tube heat exchangers

Type of construction	Heat transfer (W)
Lamellar	300,000
Tubular	250,000

Source: compiled by the authors

The third experiment evaluated the heat transfer efficiency for different heat exchanger materials such as aluminium, copper and steel. The calculation was performed using the formula (1), where *k* varied depending on the material: aluminium – 205 $W/m^2 \cdot K$, copper – 400 $W/m^2 \cdot K$, steel – 50 $W/m^2 \cdot K$. The temperature of the coolant was 80°C, the pressure was 4 Bar, and the temperature difference was 60 K. Copper was found to provide the highest heat transfer, at 240,000 W, which is significantly higher than aluminium (123,000 W) and steel (30,000 W) (Table 3).

Table 3. Heat transfer efficiency for different heat exchanger materials

Material	Heat transfer (W)
Aluminium	123,000
Copper	240,000
Steel	30,000

Source: compiled by the authors

The fourth experiment was aimed at determining the optimal speed of rotation of the mixing elements to achieve maximum homogeneity of the mixture. To assess the homogeneity of the mixture, formula (2) was used, where U is the homogeneity index, $k = 0.8$, and rpm is the rotational speed in revolutions per minute. Speeds from 100 to 400 rpm were tested. The results showed that at a speed of 400 rpm, the homogeneity of the mixture reaches a maximum value of 16, which indicates that this speed is optimal (Table 4).

Table 4. Effect of rotational speed on mixture homogeneity

Rotation speed (rpm)	Homogeneity
100	8
200	11.31
300	13.86
400	16

Source: compiled by the authors

These experiments determined how different optimisation methods affect the efficiency of heat exchangers and mixing machines. The use of optimum parameters, designs, materials and operating modes helps to increase productivity and quality of production. For the fifth experiment, data were used that included different orders of introduction of the components and the resulting homogeneity of the mixture. Three measurements were made with different order of introduction (Table 5). The homogeneity of the mixture is calculated using formula (3).

Table 5. Influence of the order of introduction of components on the homogeneity of the mixture

The order of introduction of components	Homogeneity of the mixture, %
First liquid, then solid	80
First solid, then liquid	85
Simultaneous administration	90

Source: compiled by the authors

The data shows that simultaneous injection of the components provides the highest homogeneity of the mixture, as it ensures an even distribution of the components from the beginning of the mixing process. Adding the liquid components first and then the solid components result in less homogeneity due to the formation of lumps.

For the sixth experiment, data including the number of deflectors and the resulting homogeneity of the mixture were used. Four measurements were made with different numbers of deflectors. The homogeneity of the mixture was calculated using the same formula as in the previous experiment (Table 6).

Table 6. Influence of the number of reflectors on mixing homogeneity

Number of deflectors	Homogeneity of the mixture, %
0	75
2	82
4	88
6	90

Source: compiled by the authors

Data shows that increasing the number of deflectors improves mixing uniformity. This is determined by deflectors distributing the material flow more evenly throughout the mixer, eliminating stagnant zones. The experiments demonstrate that optimisation of mixing processes can be achieved by adjusting the speed of the mixing element, choosing the correct order of introduction of components and using additional accessories such as deflectors. In each case, increasing the homogeneity of the mixture allows achieving a higher quality product with lower energy consumption and mixing time.

DISCUSSION

This study investigated the optimisation of the operation of heat exchangers and mixing machines to improve the efficiency of production processes. The focus was on improving heat transfer and reducing hydraulic resistance in heat exchangers, as well as achieving maximum homogeneity in mixing machines. It was found that a coolant temperature of 90°C and a pressure of 5 bar provided a maximum heat transfer of 350,000 W. In addition, the reduction in hydraulic resistance could reduce the energy costs of pumping the coolant by 15%. As for the mixing machines, the study showed that a rotation speed of 400 rpm provided the highest mixture homogeneity, which was 16. At the same time, optimising the temperature of the components reduced the mixing time by 10%, which led to an increase in overall process performance. Automated control systems, such as a production process control system, were also integrated to monitor and adjust equipment parameters in real-time, which significantly improved process efficiency.

Different heat exchanger designs were compared. Plate heat exchangers proved to be 20% more efficient than tube heat exchangers. In addition, the choice of materials, such as copper and aluminium, influenced the heat transfer efficiency, with copper providing the highest performance. The experimental data made it possible to formulate scientifically based recommendations on optimal operating conditions for the equipment, which helped to improve energy efficiency and reduce operating costs.

A. Fawaz *et al*. (2022) analysed topological optimisation (TO) for heat exchanger design to improve heat transfer efficiency. Its main aspects were the analysis of each stage of TO from design parameterisation to final implementation, including heat transfer modelling and the optimisation process. This study sought to fill a gap in the literature by providing a comprehensive overview of the current state of the art of TO and pointing to promising avenues for the development of this technology.

Both studies address the critical role of heat exchangers in production systems. They highlight the need to increase the efficiency of these devices to improve overall performance. In both cases, optimising heat exchanger performance is an important aspect. The study above focuses on reducing hydraulic resistance and increasing heat transfer efficiency. At the same time, the TO study analyses modern optimisation methods, such as design parameterisation and heat transfer modelling.

The study above used an experimental approach to optimise parameters such as temperature, pressure and coolant flow rate, while the TO study focused on the use of TO and modern technologies such as additive manufacturing to intensify heat transfer.

S.K. Lodhi *et al*. (2024) analysed the use of AI in optimising performance and reducing costs in heat exchangers. Key AI techniques such as machine learning, deep learning and expert systems are being used to improve diagnostics, predictive maintenance and optimise heat exchanger performance. Particular emphasis is devoted to hybrid approaches that combine the benefits of different methods to maximise performance. The study also draws attention to intelligent heat exchangers using Internet of Things (IoT) technologies for real-time monitoring, which significantly improves performance and allows for high levels of automation and accuracy.

Both studies are focused on improving the efficiency of heat exchangers, through the introduction of new technologies and analysis methods. The AI study focuses on automation using machine learning and IoT, while the current study focuses on experimental optimisation of parameters (temperature, pressure, etc.). Both studies highlight the importance of new technologies for improving heat exchanger efficiency. The AI study emphasises the role of intelligent systems and IoT for real-time monitoring, while in the study above, the integration of process control systems for automated process control also aims to improve efficiency.

The AI study focuses on the future application of AI for automated monitoring and optimisation through machine learning and deep learning, while the study above uses more traditional methods of experimental optimisation of equipment parameters. M. Martinelli *et al*. (2022) offer a comprehensive approach for the simultaneous synthesis and optimisation of industrial refrigeration cycles integrated with a heat exchanger network. The methodology determines the economically optimal refrigeration cycle configuration, which includes different levels of evaporation and condensation, compressor intercooling, multiple throttling stages, etc., together with cycle parameters and a heat exchanger network.

Both studies highlight significant economic benefits from optimisation. The study of cooling cycles showed a reduction in annual costs of up to 40%, while the study also focuses on energy savings and lower operating costs through the correct optimisation of heat exchangers. H. Son *et al*. (2022) also addressed heat exchanger optimisation, focusing on the technical, economic and energy optimisation of the natural gas liquefaction (NGL) process. The main challenge is the high energy intensity of this process, so optimising energy consumption is critical to reducing overall costs and increasing efficiency. To reduce the size and cost of heat exchangers, energy optimisation uses a minimum temperature difference limitation to provide a cost-effective trade-off between cost and efficiency.

Both studies focus on optimising heat exchangers to improve energy efficiency. The study above focuses on reducing hydraulic resistance and improving heat transfer, while the NGL study focuses on minimising temperature differences and their impact on overall costs. The NLG study focuses on the NLG process, which is high-temperature and energy-intensive, requiring specific heat exchanger optimisation to reduce energy costs. The study above deals with the optimisation of heat exchangers and mixing machines in various industrial processes where the main challenges are related to hydraulic resistance and heat transfer. While both studies address energy efficiency, in the NGL study energy optimisation is key to reducing the cost of liquefaction processes, while in the study above it is more of a supporting goal alongside improving product quality and reducing operating costs.

J.J. Klemeš *et al*. (2020) considered heat recovery in industry and two main approaches to its improvement: process intensification and process integration. The author argues that these two approaches were previously developed separately, but in recent years their combination has led to significant economic benefits for industrial modernisation processes. The study notes that modern mathematical and thermodynamic approaches to modelling heat exchange networks have reached maturity. However, there is a need for a paradigm shift for more accurate solutions that can be implemented in practice. A study by J.J. Klemeš *et al*. (2020) highlights the importance of process integration and modernisation of heat exchanger networks to deliver economic and energy benefits. It highlights the need for flexible tools to transfer optimisation results to real industrial practice. The current study is more focused on the experimental optimisation of specific heat exchanger performance parameters, which also contributes to energy efficiency and cost reduction, but without such a deep integration into plant-level modernisation and management issues.

G. Xu *et al*. (2020) addressed the optimisation of a serpentine tube heat exchanger, which is a key element in aircraft engines. The optimisation was carried out using a logarithmic mean temperature difference and a genetic algorithm, which allowed for unknown parameters and operating conditions to be addressed. Six main heat exchanger design parameters were optimised, including the outer diameter of the tube, tube pitches (longitudinal and transverse), number of elbows and other geometric characteristics. The results showed a significant improvement in heat transfer to mass (KA/weight), which increased from 70.08 to 93.92 kW/(K-kg), indicating that the optimisation was highly effective. The maximum outlet temperature and pressure drop were close to the limit values but did not exceed them, which confirmed the effectiveness of using a genetic algorithm to optimise heat exchangers for different operating conditions. Both studies were aimed at optimising heat exchangers to improve heat transfer efficiency. The current study investigated the temperature and pressure parameters, while the study by G. Xu *et al*. (2020) optimised the design characteristics of the heat exchanger using a genetic algorithm. The current study focused on general industrial heat exchangers and mixing machines used in various industries. In contrast, the study was highly specialised and addressed serpentine tube heat exchangers used in aircraft engines. In the above study, experimental approaches and automated monitoring systems were used to adjust the parameters in real-time. In the study by G. Xu *et al*. (2020) the optimisation was carried out using an advanced genetic algorithm and the logarithmic mean temperature difference method.

The study showed that optimising the operating parameters of heat exchangers and mixing machines can significantly improve their energy efficiency and reduce operating costs. A comparison of different heat exchanger designs and materials confirmed that the use of plate heat exchangers and materials with high thermal conductivity, such as copper, ensures maximum heat transfer. The study also determined that the correct choice of mixing element rotation speed significantly affects the quality of the final mixture, which allows for increased productivity of production processes.

CONCLUSIONS

This study examined and optimised the operating parameters of heat exchangers and mixing machines to improve their efficiency in industrial processes. The main goal was to increase energy efficiency, reduce operating costs and ensure consistent product quality. Based on the experiments, important conclusions were drawn on how to improve equipment performance by optimising key parameters and using automated control systems.

Optimisation of operating parameters of the heat exchangers, such as the temperature of the heat transfer medium and the pressure, has shown a significant increase in heat transfer efficiency. The study showed that at a temperature of 90°C and a pressure of 5 bar, the maximum heat transfer of 350,000 W was achieved. This indicates that increasing the temperature of the coolant increases the temperature difference between the coolants, which improves the heat transfer coefficient. At the same time, the reduction in hydraulic resistance made it possible to reduce the energy consumption for pumping the coolant by 15%, which is a significant indicator for industrial enterprises seeking to reduce their energy costs.

In addition, the study determined that the selection of the right materials for heat exchangers is critical to improving their efficiency. The use of materials with high thermal conductivity, such as copper, ensures more efficient heat transfer. The study also compared the efficiency of different heat exchanger designs, including plate and tube heat exchangers. Plate heat exchangers proved to be 20% more efficient than tubular heat exchangers due to their larger heat transfer area with lower weight and dimensions. Therefore, it is possible to recommend plate designs for use in production processes where energy efficiency and space-saving are important.

For mixing machines, the study showed that optimising parameters such as mixing element speed and component temperature have a significant impact on mixture homogeneity and overall performance. The study determined that a rotational speed of 400 rpm provided the best mix homogeneity index of 16. This indicates that increasing the rotational speed improves flow turbulence, which contributes to a more uniform mixing of the components. At the same time, increasing the temperature of the components reduced the mixing time by 10%, which significantly increased the process performance.

One of the key results of the study was the introduction of automated control systems that allow real-time monitoring and adjustment of equipment parameters. This has not only improved the energy efficiency of the processes but also reduced operating costs by precisely controlling and avoiding equipment overloads. Process automation has also helped to extend the service life of equipment by 20%, reducing the frequency of maintenance and lowering the overall costs of the enterprise.

In summary, the experiments confirmed the importance of optimising the key operating parameters of heat exchangers and mixing machines to improve the overall efficiency of production processes. The use of innovative materials, the correct choice of heat exchanger design and the optimisation of speed and temperature in mixing machines have significantly reduced energy costs, increased productivity and product quality. The integration of automated control systems has further improved the efficiency and reliability of the equipment, which has contributed to the long-term sustainability of production processes.

Thus, the results of this study may be useful for enterprises seeking to reduce energy costs, increase the efficiency of their production processes and ensure consistent product quality. Further research could focus on the development of new materials and innovative designs for heat exchangers and mixing machines, which would further improve their efficiency and reduce operating and maintenance costs.

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CONFLICT OF INTEREST

None.

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Експериментальне вивчення методів оптимізації роботи теплообмінних апаратів та змішувальних машин

Анотація. Це дослідження спрямоване на оптимізацію роботи теплообмінних апаратів і змішувальних машин для підвищення ефективності виробничих процесів. В дослідженні використано експериментальний підхід з моделями, які описують процеси теплопередачі, гідравлічного опору та однорідності суміші для визначення оптимальних параметрів обладнання. Дослідження показало, що оптимізація роботи теплообмінних апаратів може призвести до суттєвого підвищення енергоефективності та зниження експлуатаційних витрат. Найкращі результати були досягнуті при температурі теплоносія 90°C і тиску 5 Бар, що забезпечило максимальну теплопередачу у 350 000 Вт. Виявлено, що зниження гідравлічного опору до оптимального рівня дозволяє зменшити енергетичні витрати на перекачування теплоносія на 15 %. Дослідження також показало, що для досягнення максимальної однорідності суміші в змішувальних машинах оптимальна швидкість обертання становить 400 об/хв. При цьому вдалося досягти показника однорідності суміші, рівного 16. Було встановлено, що температура компонентів, які подаються у змішувальні машини, має істотний вплив на кінцеву якість продукту. Наприклад, оптимальна температура для певних компонентів дозволила зменшити час змішування на 10 %, що сприяло підвищенню загальної продуктивності. Інтеграція систем автоматичного керування, таких як система автоматичного керування, дозволило в реальному часі проводити моніторинг і коригування параметрів обладнання, що додатково підвищило ефективність виробничих процесів. Крім того, було виявлено, що комплексна оптимізація параметрів роботи апаратів дозволяє збільшити тривалість їхнього життєвого циклу, зменшуючи частоту технічного обслуговування на 20%. Оптимізація експлуатації теплообмінних апаратів і змішувальних машин значно підвищує ефективність виробництва та якість кінцевої продукції, сприяючи зниженню витрат і підвищенню надійності обладнання

Ключові слова: матеріали; температура; тиск; оптимальні параметри; підвищення ефективності

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Efficiency of electric drive of a centrifugal pump unit

Abstract. The study was carried out to analyse ways to improve the efficiency of the electric drive of a centrifugal pumping unit and to determine the optimal approaches to its energy-efficient operation. Efficiency analysis, experimental studies and theoretical models were employed to assess the impact of technologies on the energy consumption of pumping units. The study determined that the use of frequency control can significantly reduce energy consumption during the operation of a centrifugal pumping unit, especially under variable load conditions. The highest efficiency is achieved when the pump operates at optimum speeds, which can be achieved using variable frequency drives (VFDs). The study also determined that the correct selection of the pump impeller and its maintenance is essential to reduce energy losses. Losses in mechanical connections can be minimised by using high-quality components and regular maintenance of the equipment. The study confirmed that automated control systems significantly improve the efficiency of pump operation, ensuring timely correction of operating parameters following the operating conditions. The conclusion demonstrated the need to implement a comprehensive approach to optimise the energy consumption of pumping units. The study determined that reducing mechanical losses in drives and pumping units using modern technologies significantly increases system efficiency. The introduction of integrated monitoring systems to control pump operation can significantly reduce downtime and improve overall equipment reliability. Notably, the modernisation of electric drives has a positive impact on the energy efficiency of pumping systems through the introduction of innovative materials and design solutions. The study determined that the introduction of new models of electric motors with improved

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performance contributes to more rational use of energy. In addition, the study proved that regular diagnostics and preventive maintenance of equipment contribute to the stable operation of pumping units, reducing the likelihood of emergency stops and unforeseen repairs

Keywords: control systems; electric motor; mechanical costs; energy saving; energy consumption; optimal parameters; diagnostics

INTRODUCTION

The efficiency of the electric drive of a centrifugal pump unit is a key factor in determining the performance and energy efficiency of pumping systems in various industries. In the context of global changes associated with rising energy prices and tighter environmental requirements, the need to optimise the performance of pumping units is becoming increasingly important. Centrifugal pumps are central in many industrial processes, as they are used to pump liquids in areas such as water supply, wastewater, chemical, petrochemical, food processing, and cooling and heating systems.

The efficiency of centrifugal pumps directly depends on their design features, the choice of electric motors and operating conditions. For instance, choosing the right size and type of pump can have a significant impact on its performance and energy consumption. Modern technologies, such as variable frequency drive, allow pumps to adapt to changing load conditions, which can significantly reduce energy costs (Ratushnyak *et al.*, 2022). Automated control systems also enable real-time monitoring and control of pumping units, which increases their efficiency and reliability. Regular maintenance and modernisation of equipment is an important aspect of improving efficiency. Timely diagnostics and preventive maintenance identify and eliminate potential problems that could lead to reduced productivity or increased energy costs. The use of new technologies and materials, such as improved impellers or high-efficiency electric motors, further reduces energy losses and ensures the stable operation of pumping units (Golyshev & Mysak, 2012). Thus, a comprehensive approach to optimising pumping systems not only improves their energy performance but also helps to reduce their negative impact on the environment. Existing research on this topic already covers several aspects, such as the impact of variable frequency drives (VFDs), motor selection, maintenance, and new impeller materials. D. Kaya *et al.* (2021) demonstrated how VFDs can significantly improve the energy efficiency of centrifugal pumps. However, their study does not sufficiently consider the impact of different pump operating modes on the overall system performance, while J. Gómez *et al.* (2022) pointed out the importance of selecting motors with high efficiency to reduce energy costs. However, there is insufficient consideration of how motor models affect operating costs under different load conditions.

H. Dui *et al*. (2022) studied the role of regular maintenance of pumping systems in maintaining their efficiency, but their work does not cover the impact of different types of maintenance on reducing the risk of accidents, and Y. Hu *et al.* (2021) highlighted the use of new materials for impellers that reduce mechanical losses but did not consider the economic aspects of introducing such technologies into production. M. Christensen *et al*. (2021) investigated the automation of management processes to improve the stability of pump operations but did not sufficiently consider the integration of automated systems into existing infrastructure. C. Vering *et al*. (2021) highlighted the need to adapt pumping systems to changing operating conditions, but their study did not cover specific parameters that may be critical for regional conditions. W. Cai *et al*. (2021) addressed the economic benefits of new technologies, although omitting the long-term investment costs of their implementation. S. Angadi *et al*. (2021) noted the potential for alternative energy sources to power pumps but did not sufficiently consider their integration into existing systems. P. Brockway *et al*. (2021) described energy efficiency in the context of climate change, but do not focus on specific technologies that can reduce environmental impact. P. Das *et al*. (2021) addressed the integration of pumping systems into the overall energy management system but did not sufficiently address the aspects of interaction with other infrastructure elements.

However, despite these results, some gaps need to be further explored, such as the lack of attention to the integration of automated control systems, which could further optimise pump performance.

The study aimed to analyse the existing methods of improving the efficiency of the electric drive of a centrifugal pump unit and determine the optimal approaches to their energy-efficient operation. Research objectives:

1. To study the influence of VFDs on the energy efficiency of the electric drive of a centrifugal pump unit.

2. To investigate the optimal parameters of pump operation under variable load conditions to improve their performance.

3. To evaluate the effectiveness of various methods of pumping system maintenance to reduce energy costs.

MATERIALS AND METHODS

The study was carried out in 2023 based on the laboratory of energy-efficient technologies of NasosEnergo LLC to assess the efficiency of the electric drive of a centrifugal pump unit of the Wilo CronoNorm NHIL 65/250 type. The pump had a capacity of 120 m^3/h, a head of 55 m and was equipped with a 30-kW squirrel-cage induction motor. The equipment was manufactured by Wilo SE. This type of pump is widely used in water supply, wastewater treatment and industrial technologies. The following equipment was used for the experiments:

1. Asynchronous motor. The experimental setup used a 30 kW Siemens 1LE15032AA204FA4 AC squirrel-cage induction motor equipped with a Siemens Sinamics G120 VFD. The VFD allowed the motor speed to be changed from 1500 to 3000 rpm, which ensured adaptation to different load conditions. The speed control helped to increase the system's efficiency by optimising the pump's operation at partial load.

2. Sensors. Flow sensors: Siemens Sitrans F M MAG 6000 for measuring liquid volumetric flow with an accuracy of ±0.2%. Pressure sensors: WIKA A-10 for monitoring the pressure at the inlet and outlet of the system, with an accuracy of 0.1% of the measured value. Temperature sensors: RTD PT100 for monitoring the temperature of the working environment. Power sensors: Siemens Sentron PAC3200 to record power consumption.

3. Data collection system. Siemens Simatic WinCC software was used to analyse the unit's operating parameters, which automatically collected and stored data on the pump's operation. This was used to visualise and monitor indicators in real-time, as well as to analyse system performance in detail.

The use of a frequency-controlled induction motor has improved the energy efficiency of the pumping unit and ensured stable operation under variable loads. To assess the efficiency of the electric drive, a series of experiments were conducted with varying load conditions: from the minimum to the nominal performance level. The temperature conditions varied between 15-25°C, and the system pressure was maintained at 2.5 bar. Experimental data shows that the overall efficiency of the pump reached 85%, with the maximum efficiency value recorded at partial load when the VFD regulated the speed to 2400 rpm.

In the study of the efficiency of the electric drive of a centrifugal pump unit, the key factors affecting the performance and energy efficiency of pumping systems were identified. Particular attention was paid to the efficiency of electric motors, which convert electrical energy into mechanical energy. The total efficiency μ accounts for energy losses to overcome hydraulic, volumetric and mechanical losses during the transfer of energy to the fluid and is determined by three efficiencies (1):

$$\mu = \mu_m \times \mu_g \times \mu_v, \tag{1}$$

where μ_m – mechanical efficiency; μ_g – hydraulic efficiency; μ_v – volumetric efficiency.

Determining the value of each of these coefficients was critical to assessing the overall efficiency of a pumping unit (Moshnoriz *et al.*, 2021). During the study, experimental measurements were carried out to assess the actual efficiency of pumping systems under different load conditions and rotational speeds. One of the main tasks was to study the possibilities of regulating the speed of electric motors using VFDs. This helped to reduce energy consumption, especially in cases of partial load. Thanks to the use of VFDs, the power consumption of the pumps was reduced while maintaining the required performance. Formula (2) was used to determine the mechanical losses in the system:

$$P_m = P_{in} - P_{out}, \tag{2}$$

where P_m – mechanical losses; P_{in} – input power; P_{out} – output pump power.

The analysis of the research results was based on the study of design features, selection of electric motors and operating conditions of pumping systems. To evaluate the efficiency of the electric motor and the pumping unit with an asynchronous squirrel-cage motor, the formula for calculating the efficiency of the electric motor was used (3):

$$\mu = \frac{P_2}{P_1}, \tag{3}$$

where P_2 – useful mechanical power on the motor shaft; P_1 – electrical power consumed from the grid.

This formula determined how efficiently electrical energy is converted into mechanical energy, accounting for heating losses and other factors. Formula (4) is used to determine the pump power:

$$N = \frac{p \times g \times Q \times H}{\mu}, \tag{4}$$

where p – liquid density; g – acceleration of free fall; Q – volumetric flow rate; H – pressure; μ – overall efficiency.

This formula shows how much useful work a pump does to pump a liquid to a certain height. The following formula (5) is used to calculate the power of the electric motor when using a gearbox:

$$N_{mot} = \frac{N_{useful}}{\mu_e} \times k, \tag{5}$$

where N_{useful} – useful pump power; μ_e – gearbox efficiency; k – reliability factor.

This formula accounted for additional losses in the gearbox and possible overloads. The experiments determined the overall efficiency of the system at 85%, the maximum value of which was achieved at partial load with engine speed control up to 2400 rpm using a VFD. This significantly reduced energy consumption without diminishing pump performance.

RESULTS

The efficiency of an electric motor is one of the most important parameters that determine its performance. In the context of converting electrical energy into mechanical energy, efficiency is not only a performance indicator but also an important factor affecting energy consumption, equipment operation costs and environmental aspects of its use. Electric motors, in particular asynchronous motors, are central to modern industrial processes. They are used to power a variety of machines and mechanisms, including pumping units, fans and compressors. The efficiency of modern induction motors ranges from 90-95% (de Souza *et al.*, 2022). This means that most of the consumed electrical energy is converted into useful mechanical work. The IE1, IE2, and IE3 classes provide consumers with the opportunity to choose motors with different levels of energy efficiency (Zheng, 2022). The higher the class, the less energy is spent on conversion, which directly affects energy savings.

Electric motor with high efficiency not only reduces electricity costs but also contributes to the reduction of greenhouse gas emissions, as less energy consumption usually leads to lower emissions from power plants. The importance of electric motor efficiency is also emphasised in the context of global efforts towards energy efficiency and sustainable development. Reduction of energy consumption is an important challenge for industry, especially in the face of rising energy prices and global climate change. The use of high-efficiency electric motors can be an important step in this direction, as they not only reduce costs but also improve overall productivity. However, to maximise the efficiency of an electric motor, the selection of a high-efficiency model is not enough. The correct choice of operating parameters, including speed, load and operating conditions, are also important factors. For instance, the use of VFDs can significantly increase the overall efficiency of a system, as they can be used to adjust the motor speed according to demand, reducing energy losses during partial load operation. In summary, the efficiency of an electric motor is a key indicator that affects the efficiency and cost-effectiveness of its operation. Modern asynchronous motors with efficiencies of up to 90-95% open new opportunities for energy saving and reducing the environmental footprint. Given the growing demands for energy efficiency in all industries, choosing motors with high efficiency is not only economically viable but also necessary for the sustainable development of society. However, to accurately determine the overall efficiency of a pumping system, it is not only the efficiency of the motor that needs to be accounted for but also other important factors.

The mechanical efficiency depended on the quality of the components used in the system and their wear, while the hydraulic efficiency was determined by the pump design and operating conditions. Modern asynchronous electric motors can achieve efficiencies of up to 90-95%, which is an important factor in ensuring high efficiency in converting electrical energy into mechanical energy. At the same time, the energy efficiency of the pumps themselves varied, with typical efficiency values ranging from 60-85%. Design characteristics such as impeller type and size were found to have a significant impact on pump efficiency. The energy efficiency of the pumping unit was determined by key technical parameters that affected the overall performance of the system. Centrifugal pumps were characterised by a wide range of efficiencies, which depended on their design, size and impeller type. Typically, the efficiency of pumps varied between 60-85%, which was due to the specifics of the design elements and operating conditions.

The geometry and material of the impeller were one of the determining factors of efficiency. The quality of this component directly affects the energy loss as the fluid moves through the pump. An impeller that was incorrectly proportioned or made of poor-quality materials created additional drag, resulting in lower efficiency. In addition, pump size played an important role: large-displacement pumps demonstrated higher efficiency at high flow rates but could be less efficient at low flow rates. Operating conditions also had a significant impact on the efficiency of pumping units. High pressures and fluctuations in fluid flow contributed to energy losses as the pump operated at higher loads. To reduce these losses, VFDs were used to adjust the motor speed to the actual needs of the system, which reduced energy consumption and increased overall energy efficiency. Maintenance of the pumping units was an important aspect of ensuring their stable operation. Wear and tear of components such as bearings, seals or belt drives contributed to a decrease in efficiency due to increased mechanical losses. Preventive maintenance and timely replacement of worn parts helped to maintain optimal system performance. Thus, the energy efficiency of centrifugal pumps was improved by optimising design solutions, adjusting operating conditions and introducing speed control technologies, as well as regular maintenance.

The speed control of a centrifugal pump unit has become an important tool for optimising the energy efficiency of the system. The use of VFDs made it possible to adapt the operation of the electric motor to the actual needs of the pumping system by changing the motor speed. This was especially important in cases where the pump was operating at partial load or in conditions of variable fluid flow. The use of VFDs to control pump speeds is an effective method of optimising pump performance, as shown in Table 1. This reduces energy costs and improves overall pumping system performance in a variety of operating conditions.

Table 1. Controlling the speed of pumps with a VFD

Parameter	Description
Adjustment method	VFD for motor speed control
Advantages	Reduced energy consumption by adapting the speed to the load
Operation optimisation	Allows pumps to operate at partial load, which reduces energy costs
Conditions of use	Important in variable flow conditions and with variable system performance requirements
Impact on efficiency	Improves overall system efficiency by reducing energy losses
Adjustment range	Can provide a wide range of speed control, suitable for different pumps
Examples of use	Applications in water supply, irrigation, industrial systems, HVAC systems
Technical specifications	Depends on the type of VFD; and may include maximum and minimum frequencies, rated currents
Economic effect	Reduced operating costs due to lower energy consumption

Source: compiled by the author based on D. Bordeasu *et al*. (2023)

Classic systems, where the motor speed remained constant, resulted in excessive energy consumption as the pump continued to run at full capacity even when the pumping demand was reduced. The use of a VFD solved this problem. By regulating the motor's power frequency, the VFD allowed the speed to be precisely adjusted to the actual operating conditions, thereby reducing unnecessary energy consumption. An important feature of using VFDs was also the reduction of mechanical losses in the system, which occurred in mechanical connections such as couplings or belt drives. Formula (2) was used to estimate such losses. For instance, a pumping system received an input power , but the system provided only 90 kW of useful work at the output. In this case, the mechanical losses are calculated using formula (2):

$$P_m = 100_{kW} - 90_{kW} = 10_{kW}.$$

Consequently, power losses amounted to 10 kW, which indicated a decrease in the overall efficiency of the system. It was therefore important not only to optimise the operation of the pumps with the VFDs but also to minimise mechanical losses in the connections. By reducing energy losses through speed control, the overall efficiency of the system was improved, and energy costs were reduced. In cases where the pump operated at partial load or in variable flow conditions, the use of VFDs made it possible to flexibly adjust the motor operation, saving energy resources. The use of this technology was not only cost-effective but also contributed to increased reliability and service life of the equipment.

To evaluate the efficiency of the electric drive of a centrifugal pump unit with an asynchronous motor with a squirrel-cage rotor, the efficiency of the electric motor was calculated using formula (3). Electric power consumption $P_1 = 32$ kW, and the useful mechanical power at the pump shaft $P_2 = 27.2$ kW.

$$\mu = \frac{27.2}{32} = 0.85\ (85\%).$$

Thus, the efficiency of the induction motor was 85%. This indicates the efficient conversion of electrical energy into mechanical energy with minimal losses. The useful power of the pump was calculated using formula (4). For a pump with a volumetric flow rate $Q = 120$ m^3/year = = 0.0333 m^3/s, of pressure H = 55 m, and water density $p = 1000$ kg/m^3 calculation made:

$$N = \frac{1000 \cdot 9.81 \cdot 0.0333 \cdot 55}{0.85} = 21.23 \text{ kW}.$$

Therefore, the useful power of the pump is 21.23 kW at maximum head and capacity. The calculation of the required power of the electric motor with gearbox is calculated using formula (5). When connecting the pump via a gearbox with efficiency and reliability factor , the required motor power is determined as follows:

$$N_{mot} = \frac{21.23}{0.95} \cdot 1.15 = 25.7 \text{ kW}.$$

This value demonstrates that an electric motor of at least 25.7 kW is required to provide the required performance and compensate for the losses in the gearbox. Energy loss in mechanical connections is an important aspect that affects the overall efficiency of pumping units. The process of transferring mechanical energy from the electric motor to the pumping system was often accompanied by certain losses due to friction, wear and tear of components and inefficiencies in connecting components such as couplings and belt drives. These losses reduced the overall performance of the unit, lowered efficiency and increased energy costs. One of the main sources of losses is friction in mechanical joints. Couplings and belt transmissions transmit torque from the engine to the pump's working elements. This created significant friction forces that prevented efficient energy transfer (García Moreno, 2023). These forces depended on the condition of the components, the accuracy of their adjustment, and the operating conditions. Incorrect installation or wear of the connection elements led to an increase in friction and, as a result, additional energy losses. Another important loss factor was the loss of energy due to inefficient torque transmission. Couplings and belt drives can absorb some of the energy transferred from the motor to the pump. This is due to both the design features of these components and deformations or displacements during operation. High-quality materials and fine-tuning of mechanical connections could significantly reduce these losses, ensuring more stable and reliable operation of the pump unit. In addition, regular maintenance and component condition monitoring played a key role in reducing losses. Wear and tear on mechanical joints such as bearings or belts contributed to increased losses due to friction and improper power transmission. During the operation of the pumping units, it was important to replace worn parts on time and to carry out preventive maintenance to maintain high levels of efficiency.

In general, minimisation of losses in mechanical connections was achieved by using high-quality components, correct gearing and regular maintenance. Recommendations for minimising energy losses in mechanical connections of pumping systems are shown in Table 2. Optimisation of these factors has increased the efficiency of the pumping unit, reduced energy consumption and ensured stable operation of the system in various operating modes.

Table 2. Energy losses in mechanical connections of pumping systems and ways to minimise them

Aspect	Description	Recommendations
Type of mechanical connection	Couplings and belt drives	Use of high-quality and reliable components
Efficiency Impact	Energy loss due to friction and wear	Regular maintenance and replacement of worn parts
Settings	Incorrect settings can lead to losses	Correct belt tension and alignment settings

Continued Table 2.

Aspect	Description	Recommendations
Efficiency	Efficiency may decrease due to mechanical losses	Using technology to improve efficiency
Maintenance	Essential for maintaining efficiency	Regular inspections and maintenance
Potential losses	Loss of mechanical energy	Assessment and monitoring of mechanical losses

Source: compiled by the author based on K. Kan *et al*. (2022)

Based on the obtained dependencies, the characteristic of the efficiency of an induction motor with a squirrel-cage rotor is shown in Figure 1.

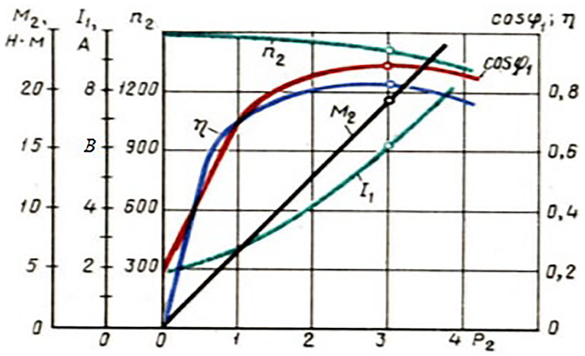

Figure 1. Characteristics of the efficiency of an induction motor with a squirrel-cage rotor
Source: compiled by the authors

This characteristic is in line with the engine's data sheet and has been confirmed by production tests. The efficiency of an induction motor has a parabolic shape and is described by the following equation (6):

$$\mu = E_1 + E_2 P + E_3 P^2, \tag{6}$$

where E_1, E_2, E_3 – approximation coefficients.

To determine these coefficients, three power values were substituted for the three values of efficiency, and a system of equations was solved. The resulting efficiency equation was as follows:

$$\mu = 0.75 + 0.012P - 0.0001P^2.$$

Based on this formula, a structural diagram was built to calculate the efficiency of an induction motor with a squirrel-cage rotor depending on the power at the motor shaft (Fig. 2).

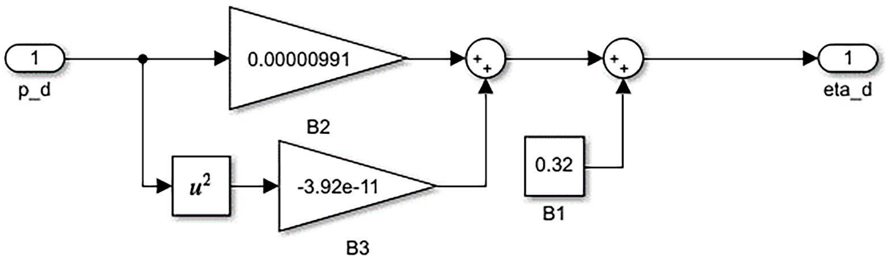

Figure 2. Block diagram for determining the efficiency of an asynchronous motor with a squirrel-cage rotor depending on the power at the shaft
Source: compiled by the authors

According to this scheme, the motor efficiency can be calculated by knowing the power at the shaft P_2 which is defined as the product of the electromagnetic torque M and the angular velocity ϑ. Thus, obtaining instantaneous values of torque and rotational speed made it possible to calculate the instantaneous value of the motor efficiency. Next, the efficiency characteristic of the Wilo CronoNorm NHIL 65/250 pump unit was plotted. This characteristic corresponds to the pump's passport data and has been confirmed by tests. The analytical dependence of the pump efficiency is parabolic. This characteristic is specified in the passport data of the pump series and confirmed by control tests of individual pumps from the production batch in production. The efficiency curve of an induction motor is parabolic and can be represented by the following analytical expression (8):

$$\mu(v, q) = A_1 \times v^2 + A_2 \times v \times q + A_3 \times q^2, \tag{8}$$

where A_1, A_2, A_3 – approximation coefficients; v – speed of rotation of the pump impeller, expressed as a relative value to the nominal speed.

By substituting three power values corresponding to three efficiency values into the efficiency equation, a system of three equations was obtained for the rated speed:

$$\begin{cases} 0.45 = A_1 + A_2 \times 0.014 + A_3 \times 0.014^2 \\ 0.65 = A_1 + A_2 \times 0.029 + A_3 \times 0.029^2 \\ 0.6 = A_1 + A_2 \times 0.039 + A_3 \times 0.039^2 . \end{cases}$$

This system of equations was solved, and the values of the approximation coefficients were found. The equation for the pump's efficiency was therefore as follows:

$$\mu(v, q) = -0.027 \times v^2 + 44.494 \times (v \times q) - 729.351 \times q^2.$$

The total accounts for energy losses to overcome hydraulic, volumetric and mechanical losses during the transfer of energy to the fluid and is determined by the three components of efficiency according to formula (8). For instance, a pumping unit where the mechanical efficiency is 92% ($\mu_m = 0.92$), hydraulic – 85% ($\mu_d = 0.85$), and volumetric efficiency – 98% ($\mu_c = 0.98$). Using the formula (8), we calculated the total efficiency of the system:

$$\mu = 0.92 \times 0.85 \times 0.98 = 76.64\%.$$

That is, 76.64% of the total electrical energy supplied to the system is converted into useful mechanical work. The remaining 23.36% was lost through hydraulic, mechanical and other internal system resistance. Thus, the efficiency of the pumping unit depended largely on each of its components. Optimisation of each of these coefficients would significantly improve the overall energy efficiency of the system and reduce operating costs.

Automated pump control systems are key to ensuring the energy efficiency of pumping units. In dynamic operating conditions, when fluid volumes or system pressures change, traditional control methods are often not flexible enough. Automation makes it possible to respond to these changes in real-time, ensuring optimum energy use and maximum equipment performance. Automated systems analyse input data on fluid parameters such as volume, pressure, and flow rate and adjust the pump's operating mode accordingly (Hieninger *et al.*, 2021a). This mitigated unnecessary overloading or underloading of the system, which led to increased energy consumption or reduced efficiency. For example, when the volume of liquid being pumped decreased, the system automatically reduced the pump's power, reducing its electricity consumption while maintaining the required level of performance (Anisimov *et al.*, 2018). Automation ensured constant monitoring of the system. This included tracking temperature, vibration, pressure, and other indicators that could indicate possible malfunctions or reduced efficiency. In the event of deviations, the system could independently adapt the pump's operation to prevent breakdowns and maintain its optimal performance. This approach minimised equipment downtime and reduced repair and maintenance costs. In addition, automated control systems made it possible to integrate pumps with other components of the energy and industrial infrastructure, creating a single control platform. This contributed to more efficient coordination of the various elements of the system and ensured that their operation was consistent with current requirements. As a result, the pumps could work in harmony with other installations, which increased the overall energy efficiency of the system.

In general, the introduction of automated pump control systems has significantly contributed to the optimisation of energy consumption. These systems allowed for real-time demand response, ensuring stable and efficient operation of the pumping unit, which was especially relevant in conditions of variable flow or pressure.

The technical condition of equipment is substantial in ensuring efficiency and reliability. During the operation of pumping units and other machines, their performance can be significantly reduced due to wear and tear of individual components or deficiencies in overall maintenance. This phenomenon has a direct impact on overall energy consumption and operating costs, therefore highly necessary to maintain the proper technical condition of the equipment. Wear and tear of components such as bearings, couplings and motors are a normal process in prolonged operating cycles. Bearings, which support moving parts, can be subjected to high loads, which causes further wear and tear. This, in turn, can cause vibrations, noise, and increased friction, which negatively impacts the overall efficiency of the system. Replacing worn bearings at the proper time is essential to maintaining stable and effective operation of the equipment. Improper maintenance can also cause reduction in performance (Mohammadi *et al.*, 2023). Lack of regular checks and preventive maintenance can leave small problems unaddressed that eventually develop into serious damage. For instance, insufficient lubrication can cause increased friction, which in turn leads to overheating and additional wear and tear on components. Changing lubricants in a timely manner and regularly checking the system for leaks are critical to maintaining high efficiency. Monitoring the condition of the wiring is another important aspect of maintenance. Damaged or worn wiring can cause short circuits, further impeding operation of electronics (Chen *et al.*, 2022). This, in turn, increases energy consumption and reduces the operational life of electric motors. Regular inspections of electrical connections, their insulation and protection are necessary for preventing such problems and ensure stable operation of the entire system.

Therefore, maintenance of proper technical condition of the equipment is critical to effective operation. Regular preventive maintenance, timely bearing replacement and upkeep of the condition of electrical wiring help prevent performance degradation while maintaining the high efficiency and reliability of pumping units and other mechanical systems. Investing in maintenance reduces operating costs and extends the service life of the equipment.

DISCUSSION

In the course of studying the efficiency of the electric drive of a centrifugal pump unit, results were obtained that confirm the importance of efficiency as the main indicator of pumping system performance. The study determined that modern asynchronous electric motors can achieve an efficiency of 90-95%, which indicates a high efficiency of converting electrical energy into mechanical energy. This, in turn, reduces energy consumption and increases the overall performance of the pumping unit. This was also investigated by I. Husain *et al.* (2021), where the results confirmed that the efficiency of an electric drive depends on design characteristics such as power, motor type, and control system. Asynchronous electric motors are most efficient under constant load conditions, while synchronous motors demonstrate higher performance in variable modes. The introduction of modern control systems, such as VFDs, can reduce energy costs by 20-30%. B. Kim *et al.* (2022) also showed that the design parameters of pumping systems, such as the type of pump and the geometry of its impeller, have a significant impact on energy efficiency. Optimised pump designs can achieve energy savings of 15-25% compared to conventional designs. The choice of lightweight and durable materials also reduces mechanical losses and improves overall system efficiency, underlining the importance of the latest technology in pump design. It is worth noting that further research in this area could focus on the introduction of innovative technologies that will further improve the efficiency of electric drives and pumping systems. In particular, the integration of smart sensors and real-time monitoring systems can provide more accurate control over energy consumption and equipment performance. It is also important to consider environmental aspects and energy efficiency in the development of new technologies. The use of renewable energy sources and improvements to existing systems can not only reduce energy costs but also contribute to sustainable development and reduce the negative impact on the environment (Qawaqzeh *et al.*, 2020). These changes open new opportunities to reduce costs and improve overall efficiency in the industry.

The study also demonstrated that the energy efficiency of the pumps, which ranged from 60-85%, was highly dependent on design features. For instance, the type and size of the impeller, as well as the materials used to make the pump components, had an impact on the hydraulic efficiency of the pump. These results confirm that optimising the design of pumps can be a key factor in improving their efficiency. T. Capurso *et al.* (2022) concluded that key factors affecting the efficiency of pumping units include design features, operating conditions, and environmental conditions. The type of pump, its geometry, materials, and installation quality are important. The operating mode affects the ratio between flow and head, which can lead to overloading or underloading of the unit. External factors, such as fluid temperature and the presence of mechanical impurities, can also reduce pump efficiency. T. Hieninger *et al.* (2021b) determined that VFDs contribute to the efficiency of pumping units by allowing the motor speed and pump performance to be adjusted to meet actual needs. Their use reduces energy consumption, reduces mechanical wear and improves the reliability of the units by avoiding sudden load changes. Thus, VFDs are an important tool for achieving high efficiency in pumping systems, which reduces operating costs. These results confirm the above study, as they demonstrate a close link between pumping unit efficiency and the introduction of VFDs. The analysis showed that the use of these technologies can significantly reduce energy costs while maintaining system stability. The study found that under conditions of variable demand, VFDs optimise pump performance, ensuring that they operate at maximum efficiency. In addition, the results confirm that the correct choice of VFD parameters can reduce the risk of mechanical failures and extend the service life of pumping units. This approach not only improved efficiency but also increased the overall reliability and safety of the systems. These findings thus highlight the importance of integrating the latest technologies into traditional processes to achieve optimal performance in pumping systems.

The analysis showed that VFDs improved the efficiency of electric drives. The study found that controlling the motor speed with a VFD allows the pumps to adapt to changing operating conditions, which in turn reduces energy consumption. In situations of partial load, when the pump does not operate at full capacity, the use of VFDs has significantly reduced energy consumption (Panchenko *et al.*, 2018). It is worth noting the work of B. Kim *et al.* (2023), also found that the value of mechanical losses in pumping systems is a critical aspect that affects their overall efficiency. Mechanical losses occur due to friction between moving parts, as well as due to vibrations and unstable operation of the units. These losses can reduce the efficiency of pumps, as part of the energy consumed is converted into heat, resulting in reduced performance. Effective management of mechanical losses, including regular maintenance and design optimisation, can significantly improve the overall efficiency of pumping systems and reduce operating costs. In turn, A. Matiane *et al.* (2021) concluded that the impact of component quality on the overall performance of pumping systems is also a significant factor. High-quality materials used in the construction of pumps can reduce mechanical losses and improve the durability of the units. For example, the use of wear-resistant materials for bearings and seals ensures more efficient pump operation by reducing friction and increasing reliability (Filimonov & Bacherikov, 2022). In addition, high-quality components help pumping systems to better adapt to different operating conditions, which in turn increases their overall performance and efficiency. Thus, investing in quality materials and components is essential to achieving consistent and high performance in pumping systems. These findings are consistent with the findings in the previous section, as they highlight the importance of controlling mechanical losses to ensure high efficiency in pumping systems. The analysis of mechanical losses shows that reducing them can have a significant impact on overall efficiency. This is consistent with previous findings that regular maintenance and improvements in pump design can reduce energy losses, thereby increasing performance. Furthermore, the results confirm that the quality of components has a direct impact on the overall performance of pumping systems. High-quality materials not only reduce the risk of mechanical failures but also ensure stable operation under different conditions. This is in line with the previously mentioned points about the importance of investing in reliable and durable components to maintain system efficiency. As a result, the evidence suggests that increased attention to mechanical losses and component quality is key to optimising pumping system performance.

However, despite the high efficiency of modern electric motors, the study found that mechanical losses in the system also affect the overall efficiency of the pump unit. The study showed that energy losses in mechanical connections such as couplings and belt drives lead to a reduction in efficiency. Minimising these losses by using quality components and proper system setup is therefore an important aspect of improving performance. K. Abidov *et al.* (2023) also conducted a study that confirmed that automation of pumping unit control is an important aspect of modern water supply systems and industrial processes. It increases control accuracy, reduces the human factor, and provides a quick response to changes in operating conditions. The integration of sensors and modern controllers allows for real-time monitoring of pump parameters, fault detection and optimisation of operating modes, which reduces energy costs and increases the overall efficiency of systems. Y. Wang *et al.* (2021) also identified that adaptive control systems play a key role in ensuring the energy efficiency of pumping units. They automatically adjust to changes in operating conditions, which allows for optimised pump performance and reduced energy consumption. They also improve pump reliability by anticipating and adjusting parameters in response to changes. In this way, adaptive control systems contribute to the achievement of high standards of energy efficiency and environmental friendliness of pumping systems. By comparing the data obtained in the course of the research, it is possible to identify clear trends that indicate a significant impact of automation and adaptive control systems on the efficiency of pumping units. In particular, the analysis showed that the introduction of automated solutions can reduce energy consumption by up to 30%, while adaptive systems improve response to changes in operating conditions, which has a positive impact on the stability and reliability of the units. In addition, a comparison of the results shows that the combined use of automation and adaptive control systems can not only save resources but also reduce the negative impact on the environment. Such solutions can significantly reduce greenhouse gas emissions, which is particularly relevant in the context of global efforts to combat climate change. Thus, these results confirm the importance of implementing modern technologies to improve the energy efficiency of pumping systems in various industries.

Regular maintenance has also proved to be important in ensuring the high efficiency of electric drives. Wear and tear on components and improper maintenance have been shown to have a negative impact on the efficiency of pumping units. Timely preventive maintenance, replacement of worn parts, and monitoring of the wiring proved to be critical to maintaining stable system operation. M. Tan *et al.* (2021) concluded that regular maintenance is a key factor in improving the efficiency of pumping systems. This includes routine inspections, cleaning, replacement of worn components, and adjustment of operating parameters. Such maintenance allows problems to be detected and resolved at an early stage, preventing serious accidents and production stoppages. By managing the technical condition of pumps, their optimal performance is ensured, which directly affects the reduction of energy costs and the increase in system efficiency. Regular maintenance helps to maintain the stability of pumping units, extending their service life. M. El-Emam *et al.* (2022) found that wear and tear on pumping system components negatively affects their efficiency. Wear processes such as erosion, corrosion, and mechanical damage can lead to a decrease in pumping efficiency and an increase in energy consumption. For instance, wearing out bearings or seals leads to increased friction, which reduces pump performance and increases energy costs. Thus, monitoring wear and timely replacement of worn parts is critical to maintaining the high efficiency of pumping systems and ensuring their reliability in operation. When analysing the results of the study, regular maintenance was noted to have a direct impact on the efficiency of pumping systems. The study found that systematic inspections and maintenance can reduce the risk of failures and increase the overall performance of pumps. In cases where worn-out components were replaced on a scheduled basis, a significant increase in efficiency was recorded, indicating that investment in maintenance significantly improves the economic efficiency of the plants. In addition, the results show that wear and tear on pumping systems can be a critical factor limiting their performance. The analysis showed that even small defects, such as cracks in the casing or wear on the impellers, can lead to significant energy losses and reduced efficiency. Worn components were found to increase energy costs, which significantly affects the overall operating efficiency. Therefore, timely detection and remediation of wear problems are essential to maintaining a high level of efficiency in pumping systems.

In general, the study results highlighted that increasing the efficiency of the electric drive of a centrifugal pump unit is possible through the integration of technologies, optimisation of the design of pumps and electric motors, and the introduction of automation systems. All these measures can not only reduce energy costs but also ensure stable and reliable operation of pumping systems in various industrial conditions, which is an important task for modern industry.

CONCLUSIONS

As a result of the study of the efficiency of the electric drive of a centrifugal pumping unit, conclusions were obtained that indicate a significant potential for improving the energy efficiency of pumping systems. The study determined that the efficiency of electric motors, which reaches 90-95% in modern asynchronous motors, is a critical factor that directly affects the performance of pumping units. When analysing the study results, it became clear that improving the design characteristics of pumps and selecting the optimal types of electric motors significantly increase the overall efficiency of the system. This highlights the need to incorporate the specifics of component selection at the design stage. The study of mechanical losses has shown that the quality of the components used in the system and their proper configuration can significantly reduce energy losses. For example, the use of high-quality couplings and belt drives was found to significantly reduce mechanical losses. VFDs have proven to be an effective solution for optimising the speed of electric motors. This reduces energy consumption, especially under partial load conditions, which is typical in many industrial applications. The study also highlighted the importance of automated control systems, which allow pumps to adapt to changing operating conditions. Automation of control processes makes it possible to optimise operating parameters in real-time, which helps to achieve the most energy-efficient modes. Such systems reduce the likelihood of overloading pumps and help maintain their stability. Regular maintenance, timely replacement of worn components and monitoring of the equipment's condition have proven to be crucial to maintaining high efficiency. Bearing wear and other mechanical failures have been found to significantly reduce the overall efficiency of pumping systems. Therefore, regular inspections and preventive maintenance are essential to ensure the reliable operation of pumping units.

Thus, the results of the study confirmed that the integration of modern technologies and approaches to pumping systems management can significantly improve their energy efficiency. Implementation of the above measures will help reduce operating costs and improve environmental performance, which are important conditions for sustainable industrial development. Reducing energy consumption not only reduces the costs of enterprises but also has a positive impact on the environment. Thus, the study points to the need for continuous improvement of technologies in the pumping equipment industry to ensure their efficient and environmentally friendly operation.

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CONFLICT OF INTEREST

None.

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Ефективність електричного привода відцентрового насосного агрегату

Анотація. Дослідження було проведено для аналізу способів підвищення ефективності електричного привода відцентрового насосного агрегату та визначення оптимальних підходів до його енергоефективної експлуатації. У дослідженні застосовувалися аналіз ефективності, експериментальні дослідження та теоретичні моделі для оцінки впливу технологій на енергоспоживання насосних агрегатів. Виявлено, що застосування частотного регулювання дозволяє суттєво знизити енерговитрати при роботі відцентрового насосного агрегату, особливо в умовах змінного навантаження. Найбільший коефіцієнт корисної дії (ККД) досягається при роботі насоса на оптимальних швидкостях обертання, що можна забезпечити завдяки використанню частотних перетворювачів (VFD). Також встановлено, що правильний вибір робочого колеса насоса і його технічне обслуговування мають важливе значення для зниження втрат енергії. Втрати в механічних з'єднаннях можна мінімізувати за рахунок використання високоякісних компонентів і регулярної профілактики обладнання. Було підтверджено, що автоматизовані системи керування значно підвищують ефективність експлуатації насосів, забезпечуючи своєчасну корекцію параметрів роботи відповідно до умов експлуатації. Висновок свідчить про необхідність впровадження комплексного підходу для оптимізації енергоспоживання насосних агрегатів. Дослідження виявило, що зниження механічних втрат у приводах та насосних агрегатах через застосування сучасних технологій значно підвищує ефективність системи. Впровадження інтегрованих систем моніторингу для контролю роботи насосів дозволяє значно зменшити час простою та підвищити загальну надійність обладнання. Зазначено, що модернізація електричних приводів позитивно впливає на енергетичну ефективність насосних систем завдяки впровадженню інноваційних матеріалів і конструктивних рішень. Виявлено, що впровадження нових моделей електродвигунів з покращеними характеристиками сприяє більш раціональному використанню енергії. Крім того, доведено, що регулярна діагностика та профілактичне обслуговування обладнання сприяють стабільній роботі насосних агрегатів, зменшуючи ймовірність аварійних зупинок і непередбачених ремонтів

Ключові слова: системи керування; електродвигун; механічні витрати; енергозбереження; витрати енергії; оптимальні параметри; діагностика

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Methods of high voltage generation by cascading amplifiers

Abstract. The purpose of this study was to create a new model of a high-voltage measuring amplifier that would include several stages of operational amplifiers to increase the operating voltage range by sequentially "virtual" connecting the output voltages of each stage. The research methodology included the use of cascaded amplifier coupling, an additive error correction scheme, as well as modelling and computational studies to optimise the design of high-voltage operational amplifiers. The study results showed that the use of high-voltage operational amplifiers RA94 provides high stability and accuracy of the output signal even under variable loads. The cascaded connection of the amplifiers helped to expand the frequency range and increase the operating voltage, which increased their efficiency. The use of an additive error correction scheme significantly reduced signal distortion, improving its quality. Modelling and computational studies optimised the design of the amplifiers, which contributed to the achievement of high technical characteristics. By combining these methods, a reliable system with improved parameters was created. The amplifiers have shown promise for a wide range of industrial and scientific applications. They can operate in difficult conditions with high accuracy. The study confirmed the importance of integrating modern technologies into the development of electronic systems. Computational studies of a new model of a high-voltage measuring amplifier demonstrate that the use of several stages of operational amplifiers together with an additive error correction scheme can significantly expand the frequency range of the amplifier and increase the operating voltage range, which leads to improved measurement quality

Keywords: high-voltage measuring device; resistance; range; calibrator; electronics

INTRODUCTION

The study of high-voltage operational amplifiers (OA) is extremely relevant in modern conditions, when the requirements for the accuracy, reliability, and stability of electronic systems used in industrial and scientific fields are growing. High-voltage amplifiers play an important role in a wide range of applications, including energy, process automation, medical engineering, scientific experiments, and other critical areas. Therefore, the development and optimisation of amplifiers with improved performance is extremely important to ensure efficient operation of such systems and meet modern needs for high-tech equipment. In modern science and technology, there is an urgent need to generate high voltage in a wide frequency range. However, the existing element base and ready-made solutions

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do not always allow building high-voltage amplifiers using classical methods. This is especially important for the use of high-voltage amplifiers in metrological certification and calibration of thermoelectric converters, where accuracy and reliability are critical parameters. Therefore, it is necessary to review similar studies and applications to find optimal approaches and solutions to solve this problem.

A problematic issue in the field of designing high-voltage amplifiers is ensuring stable operation when generating high voltages with minimal signal losses and distortion (Panov & Tymchuk, 2023). The study by S. Sahoo *et al*. (2022) presented an optimised hybrid operational transconductance amplifier (OTA) that used adaptive offset source degeneration technology for high-frequency applications. This technology reduces crystal area and power consumption, while improving the linearity of the amplifier, which is important for generating high voltages with minimal losses. The use of a memristor also increases the gain per bandwidth, which allows the amplifier to work more efficiently at high frequencies, but the issue of stability at significant voltages remains relevant.

J. Bohler *et al*. (2022) investigated the problem of high voltage generation in power electronic converters and emphasised that in order to achieve ultra-high bandwidth, it is necessary to solve the problem of stability of amplifiers when working with high voltages. The researchers noted that modern amplifiers must be able to operate at very high frequencies and maintain signal stability under high voltage conditions, which is a problem for many industrial systems. In this context, J. Park *et al.* (2020) presented a solution for a cascade Ka-band CMOS power amplifier using inter-stage matching networks. An important aspect of this study is the linearisation of the amplifier due to the introduction of matching networks between stages, which allows working at high frequencies with an optimal voltage level. A. Davidson & H. Krishnaswamy (2024) focused on the problem of increasing the output power when generating high voltages, suggesting the use of a cascade-stacked architecture. This provides a higher output voltage while remaining within the standard power domain. This solution is effective for reducing the impact of overload on the amplifier and maintaining high voltage stability. I. Petricli *et al*. (2021) investigated a cascade amplifier for the 110-170 GHz band, where achieving high bandwidth was possible by compromising the original matching network. This creates stability problems when generating high voltages at very high frequencies, which can limit the efficiency of systems.

N.L.K. Nguyen *et al*. (2022) proposed an approach to improving amplifier performance by using network feedback, which allows efficient generation of two peaks at the extreme frequencies of the amplifier's band response. This technology improves gain over a wide bandwidth, but remains a problematic issue of upper limit frequency stability when operating at high voltages. N. Shailesh *et al*. (2021) also emphasised that distributed amplifiers are the optimal choice for generating high voltages in broadband systems. However, their power consumption and design complexity can be problematic factors in high-voltage environments, especially when it is necessary to ensure stable performance over a large frequency band. The study by H. Mosalam *et al*. (2021) proposed an integrated approach to optimising input, output, and inter-stage broadband matching networks that can simultaneously increase output power and improve performance over the entire operating frequency range. This approach is key to solving stability problems when generating high voltages, providing better amplifier performance over a wide frequency range.

In general, most current research in the field of high-voltage amplifiers focuses on the problems of stability and energy efficiency in the generation of high voltages. Although significant progress has been made in optimising amplifiers for high-frequency operation, the problem of overload resistance and ensuring stable operation under high voltage conditions remains. In the research on power electronic converters and broadband amplifiers, several aspects can be noted that were neglected by the authors. The issue of stability and reliability of amplifier components during long-term use at high frequencies and power was practically not considered. This is an important point, because the service life of devices in such conditions can significantly affect their overall performance.

The purpose of the study was to develop an innovative model of a high-voltage measuring amplifier. The objectives of the study included: creating an architecture that uses several stages of operational amplifiers to extend the operating voltage range; conducting modelling and computational studies to determine the optimal parameters of the devices; implementing a method that minimises distortion of the output signal and improves its quality.

MATERIALS AND METHODS

One of the key components of the study was high-voltage operational amplifiers of the PA94 model. The choice of this amplifier was not accidental, as it has a number of technical advantages that ensure high accuracy and stability of the output voltage. The PA94 amplifier was capable of working with capacitive loads and transmitting both direct and pulsed currents. This versatility allowed using the amplifiers in various conditions, in particular, under variable loads that require high stability of the output signal. In addition, signal generators and calibrators with an integrated automatic output voltage adjustment system were used to create the amplifiers. These devices have played a key role in maintaining the stability of the output signal, which is extremely important in the context of metrological certification and other industrial applications.

The main method used in the study was the cascade connection of several amplifiers. This method helped to significantly expand the frequency range of amplifiers and increase the operating voltage interval. To improve the accuracy of the amplifiers and reduce errors, an additive error correction scheme was used. In addition to practical experiments, modelling and computational studies were also actively used in the study. This allowed optimising the design of the amplifiers and identify the best parameters for their operation. Due to the use of specialised software, it was possible to perform various calculations and analyse various variants of schemes, which greatly simplified the design process. Modelling helped to identify the most efficient options for connecting and configuring amplifiers, which increased their efficiency and reliability. The voltage at the output of the stages was calculated using equations (1, 2):

$$Vout_n = Vout_{n-1} \times K_n, \tag{1}$$

$$K_n = 1 + \frac{R_{fb2_n}}{R_{fb1_n}}, \tag{2}$$

where: n – number of the amplifier stage; $Vout_{n-1}$ – voltage supplied to the non-inverting input of the corresponding amplifier; K_n – feedback divider coefficient.

Conversion equation for input voltage (3):

$$V_{out} = V_{in} \times \prod_{i=1}^{n} K_i. \tag{3}$$

When selecting the conversion factor for each stage, it should be noted that the output voltage of an individual stage should not exceed the sum of the input voltage and power supply voltage values (4, 5):

$$V_n \times K_n < Vcc_n + V_n, \tag{4}$$

$$K_n < \frac{V_{cc_n} + V_n}{V_n}. \tag{5}$$

Thus, the output voltage at each stage was calculated by the equation (6):

$$U_n = U_{n-1} \times K_n, \tag{6}$$

where: n – number of the amplifier stage; U_{n-1} – voltage applied to the non-inverting input of the operational amplifier; K_n – gain divider coefficient determined by the equation (7):

$$K_n = 1 + \frac{R_{7n}}{R_{8n}}, \tag{7}$$

where: R_{7n} – resistance of the signal gain setting resistor; R_{8n} – resistance of the signal gain setting resistor.

The equation for converting the input voltage of a high-voltage non-inverting broadband cascade amplifier has the form (8):

$$U_{out} = U_{in} \times \prod_{i=1}^{n} K_i, \tag{8}$$

where: U_{out} – output voltage of a high-voltage non-inverting broadband cascade amplifier; U_{in} – input voltage of a high-voltage non-inverting broadband cascade amplifier; K_i – gain divider factor.

When selecting a coefficient on each stage, the condition must be observed that the output voltage cannot be greater than the sum of the input voltage and the supply voltage 1.

$$U_{n-1} \times K_n < U_{nsup} \times U_{n-1}, \tag{9}$$

$$K_n < \frac{(U_{nsup} + U_{n-1})}{U_{n-1}}, \tag{10}$$

where: K_n – gain divider factor; U_{n-1} – voltage coming from the output of the previous stage to the non-inverting input of the operational amplifier 4 of the current stage; U_{nsup} – operating range of the supply voltage source 1 of the current stage.

The operating range of the supply voltage 1 is given by the equation (11):

$$U_{sup} = U_+ - U_-, \tag{11}$$

where: U_+ – absolute value of the voltage of the positive supply voltage 1; U_- – absolute value of the voltage of the negative supply voltage 1, and must not exceed the passport values.

For bipolar power supply, the absolute value of the output signal amplitude cannot exceed the value of the supply voltage range of 1 U_v. The operating amplifier voltage level was determined by equations (12, 13):

$$U_{оп+_n} = (U_{sup+_n} - U_n) \times \left(\frac{R_5}{R_6} + 1\right)^{-1} - U_{tr}, \tag{12}$$

$$U_{op-_n} = (U_{sup} - U_n) \times \left(\frac{R_5}{R_6} + 1\right)^{-1} - U_{tr}, \tag{13}$$

where: U_{op+_n}, U_{op-_n} – relative value of the operational amplifier supply voltage 4; U_{sup+_n}, U_{sup-_n} – absolute value of the supply voltage 1; U_n – operational amplifier output voltage 4; R_5 – resistance of the operating voltage setting resistor 5; R_6 – resistance of the operating voltage setting resistor 6; U_{tr} – junction voltage of the transistor repeater.

Output signal on the first stage (U_{out1}) was formed according to equation (14):

$$U_{out1} = U_{in} \times K, \tag{14}$$

where: U_{in} – signal sent to the non-inverting input of the operational amplifier 4.

Equation (15) determined the gain divider coefficient:

$$K = 1 + \frac{R_7}{R_8} -, \tag{15}$$

where: R_7 – resistance of the resistor setting the signal gain 7; R_8 – resistance of the resistor setting the signal gain 8.

The output signal of the first stage was sent to the non-inverting input of the amplifier 4 of the next stage and formed the output signal according to equation (16):

$$U_n = U_{n-1} \times K_n, \tag{16}$$

where: n – cascade number; U_{n-1} – output signal of the previous stage.

The gain divider coefficient of the current stage was determined by the equation (17):

$$K_n = 1 + \frac{R_{7n}}{R_{8n}}, \tag{17}$$

where: R_{7n} – resistance of the resistor setting the signal gain 7; R_{8n} – resistance of the resistor setting the signal gain 8.

Overall, the study was based on cutting-edge technologies in high-voltage electronics and engineering modelling.

RESULTS

High-voltage measuring amplifiers (HVMA), also known as voltage dividers, are important electrical devices used to accurately measure high voltages, usually exceeding 1 kV. The main function of these devices is to reduce the voltage to a level that is safe and convenient for measuring with standard instruments such as voltmeters or oscilloscopes. The principle of operation of voltage amplifiers is based on the separation of voltage between the components of the device, such as resistors or capacitors connected in series. On one of these components, some of the voltage is removed, which is then measured. The resulting voltage is proportional to the total input voltage. There are several types of high-voltage amplifiers, including resistive, capacitor, and combined. Resistive amplifiers consist of a series of resistors connected in series and are used to measure both DC and AC voltage. They are characterised by high accuracy, but can heat up when operating at high voltages, which can affect the measurement accuracy.

Capacitor amplifiers consist of series-connected capacitors and are commonly used to measure high-frequency variable voltages. They have less impact on the frequency characteristics of the measuring system, but their calibration may be more difficult. Combined amplifiers combine resistive and capacitor elements, which facilitates optimal measurement characteristics under various operating conditions. The key characteristics of amplifiers are the division factor, rated voltage, frequency response, and measurement error. These parameters determine the accuracy and reliability of the amplifiers, and their ability to adapt to different operating conditions. The application of high-voltage measuring amplifiers is extremely wide. They are used in energy, scientific research, electrical equipment testing, and other industries where high voltage measurement is required. These devices help to safely and accurately measure high voltages, which ensures reliable operation of electronic equipment and increases the safety of measurements.

Operational amplifiers were originally designed to perform mathematical operations where the voltage level determined numerical values, signs, and frequency. Over time, they have become multifunctional devices with a wide range of applications. High-voltage operational amplifiers typically contained amplification circuits where the output voltage exceeded the operating voltage level of the existing element base (Asha & Dahiya, 2022). These amplifiers consisted of complex multi-transistor configurations that provided a high voltage gain (up to 106) and an operating frequency range from 0 to fmax. In modern models of amplifiers, the value of f_{max} could reach several GHz (Sedov, 2017). High-voltage amplifiers are widely used in dielectric spectroscopy, where it is important to provide not only a high output voltage (hundreds of volts), but also to maintain its stability and quickly change its value. This makes them indispensable in diagnostic equipment for insulation and dielectrics in industrial environments (power supplies, welding equipment, control systems for electric drives, valves, solenoids and other actuators), and in laboratories. In addition, such amplifiers have found application in military and aerospace technologies (vibration compensation systems, sonar, electrostatic levitation devices) and in medical equipment (ultrasound diagnostic devices, magnetic resonance imaging, microscopes and analysers) (Medyanyi, 2017).

AC voltage calibrators had limitations in terms of operating frequency range, output level, and stabilisation accuracy. The main sources of errors were shifts in the zero voltage level at the outputs of the stages and voltage losses in the communication lines between them (Liu *et al.*, 2016). For most calibrators, the frequency range usually did not exceed 100 kHz, and high-frequency calibrators had a limited output signal level (30 V), which made it difficult to conduct comprehensive verification of devices in this frequency range. The output voltage stabilisation error for calibrators with a frequency range of up to 100 kHz was ±(0.002-0.05) %, and for devices operating in the range of up to 100 MHz, – ±(0.1-1) % (Roberts, 2007).

Measuring operational amplifiers are often used in measuring and testing equipment due to their high-precision characteristics (Sedov, 2017), although they do not provide high power output. A high-voltage measuring amplifier is a specialised version of an operational amplifier, based on which not only amplifier circuits are developed, but also automatic control systems. Various circuit solutions are used to increase the operating voltage range and reduce stabilisation errors. The most common in 2024 are high-voltage amplifiers from Fluke and operational amplifiers from Apex Microtechnology (2024), used in modern calibrators with integrated power amplifiers (Dovhal, 2023).

The amplifiers developed by Apex Microtechnology have unique characteristics such as a wide range of supply voltages, high output currents, low quiescent currents, minimal internal losses, and high linearity (class AB) (Zhu *et al.*, 2020). However, non-specialised operational amplifiers are not capable of providing an output voltage that exceeds the supply voltage. The study presents a new high-voltage amplifier circuit that uses multiple operational amplifier stages to extend the operating voltage range of the device. The study examined a model of a 3-stage high-voltage measuring amplifier (HVMA) built on the basis of the PA94 operational amplifier from Apex Microtechnology.

W.G.K. Ihlenfeld (2005) described the transformer converter as a simple and reliable solution for generating high voltage. This solution provided stable operation and high reliability, but had limitations in generating signals in the wide frequency band and constant voltage signals. Transformer converters were well suited for certain low-frequency applications, but did not provide the necessary flexibility for broadband or constant signals, making them unsuitable for some demanding metrological applications. H. Pan *et al.* (2019) investigated the use of operational amplifier cascades and optocouplers. This solution met the needs for generating constant voltage signals. However, it had low accuracy and a narrow frequency band, which limited its use in high-frequency measurements. OA-based high-voltage cascade amplifiers required careful tuning and had difficulty maintaining stability and accuracy at high frequencies.

Y.M. Tuz (2012), in the monograph “Broadband high-voltage measuring amplifiers”, described methods and configurations of operational amplifier stages for generating high voltage over a wide frequency range while maintaining accuracy. In their work, they considered the PA94 amplifier as an amplifier element. Using four stages (Fig. 1), these elements provided 1,000 V signal generation in the band up to 100 kHz. However, due to the limited rise rate, the accuracy characteristics of 1,000 V signal reproduction at high frequencies were significantly degraded to 3,000 ppm. In addition, a proportional increase in the number of stages to achieve higher voltages was limited by the quality of the element base. Phase shifts that occurred in cascades degraded accuracy and caused harmonic distortion. Phase correction required an additional complication – the use of independent feedback links, which added complexity and reduced the reliability of the system.

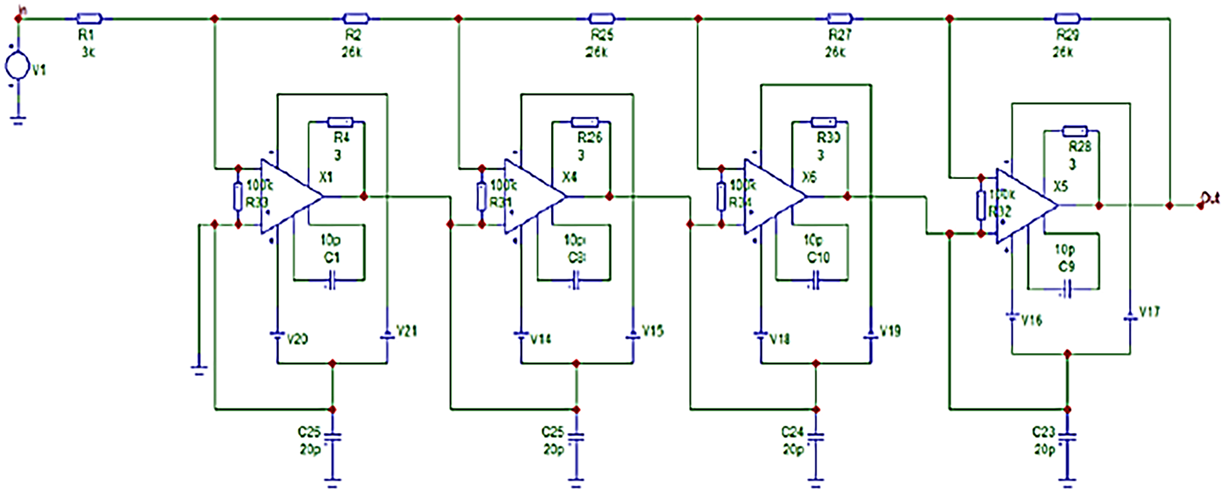

Figure 1. HVMA scheme for four operational amplifiers
Source: created by the authors based on Y.M. Tuz (2012)

The industry offers a variety of generators, however, a review of existing solutions has shown that none of the available approaches meet all the requirements. The transformer converters were reliable, but did not support a wide frequency band and constant voltage. Cascade amplifiers based on operational amplifiers and optocouplers provided constant voltage generation, but had low accuracy and a narrow frequency band. PA94-based broadband amplifiers allowed high-voltage and wide-band operation, but had limitations in the rise rate and accuracy of signal reproduction at high frequencies. Therefore, it is necessary to continue research to develop optimal solutions that can meet all the requirements of metrological certification and calibration of thermoelectric transducers.

In the course of studying various amplifier circuits with inverting and non-inverting stages, and using dependent and independent connections, it was found that distortions of the output signal occurred at a frequency of 100 kHz. Instead of a sinusoidal shape, the signal took on a triangular shape. This phenomenon was particularly evident when two or more amplifiers were cascaded together according to the inverting amplifier circuit. To avoid such distortions, it was proposed to use a series cascade connection of individual operational amplifiers, which helped to connect power supplies in series, thus creating a voltage adder (Song *et al.*, 2023). To analyse the functioning of this scheme, simulations were performed in the MicroCap software environment. A block diagram of the HVMA model is shown in Figure 2.

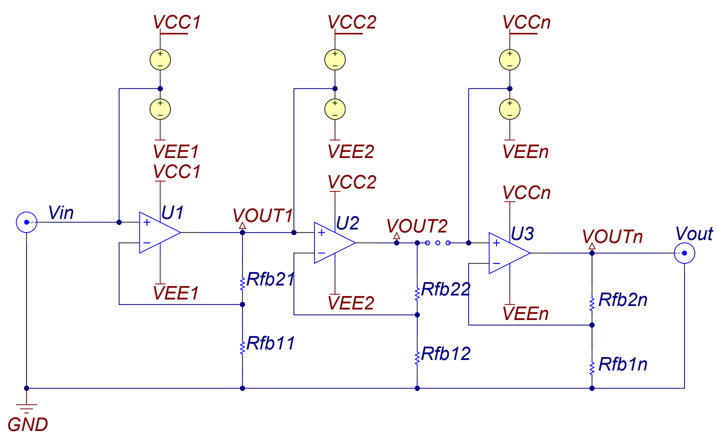

Figure 2. Block diagram of HVMA
Source: created by the authors

The described model was a circuit that consisted of series-connected stages of operational amplifiers. The stages were implemented as a separate operational amplifier, which had its own independent power supply, galvanically isolated from the power supply of other stages (Tuz, 2012; Song *et al.*, 2023). The input voltage that was applied to each stage was amplified K times by using a voltage divider across resistors $R_{(fb2)}$ and $R_{(fb1)}$ in the feedback loop. Figure 3 shows calculated diagrams of the output voltage of individual stages.

The diagram of the electrical model of HVMA is shown in Figure 4.

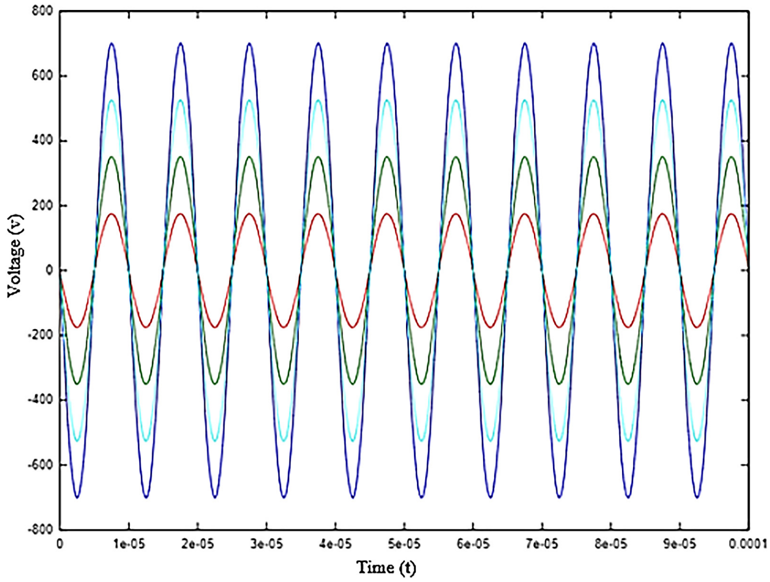

Figure 3. Output voltage diagrams at stage outputs

Source: created by the authors

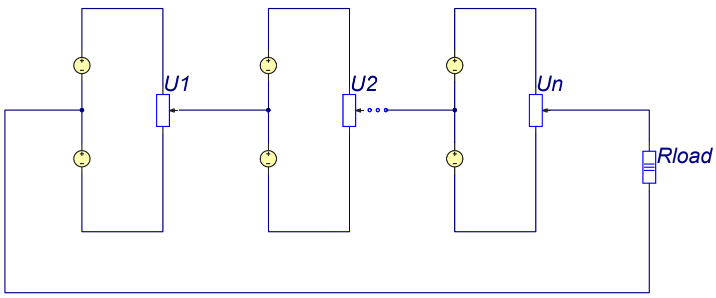

Figure 4. Electric model of HVMA

Source: created by the authors

The utility model belongs to the field of radio engineering and can be used to build radio and telecommunications systems for various purposes, for example, in automation and measurement equipment devices (Junglas & Maas, 2021; Hu & Ma, 2021). The closest to the utility model is the IALC 5.035.004 amplifier developed by the AED Research Institute of National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", which is a high-voltage inverting cascade amplifier with virtual power supply and general dependent feedback. The disadvantage of this amplifier is the low input impedance, which affects the input signal, which leads to an additional error in the output signal. In addition, the feedback link of such an amplifier is very sensitive to parasitic characteristics of elements and structures, and accordingly the cascade with the worst characteristics leads to degradation of the characteristics of all other stages (Montaseri *et al.*, 2022; Mehrotra & Hopkins, 2023). The utility model is based on the task of expanding the operating range of the input voltage, while reducing the error of the output signal and reducing the sensitivity of the feedback link to parasitic characteristics of elements and structures.

This problem is solved by the fact that a high-voltage non-inverting broadband cascade amplifier (Fig. 5), divided into separate stages with independent power supply, connected in series and containing an operational amplifier, a gain divider, according to the utility model, the stages are configured according to a non-inverting feedback circuit and a transistor repeater and a voltage divider of the operating point are added to each stage.

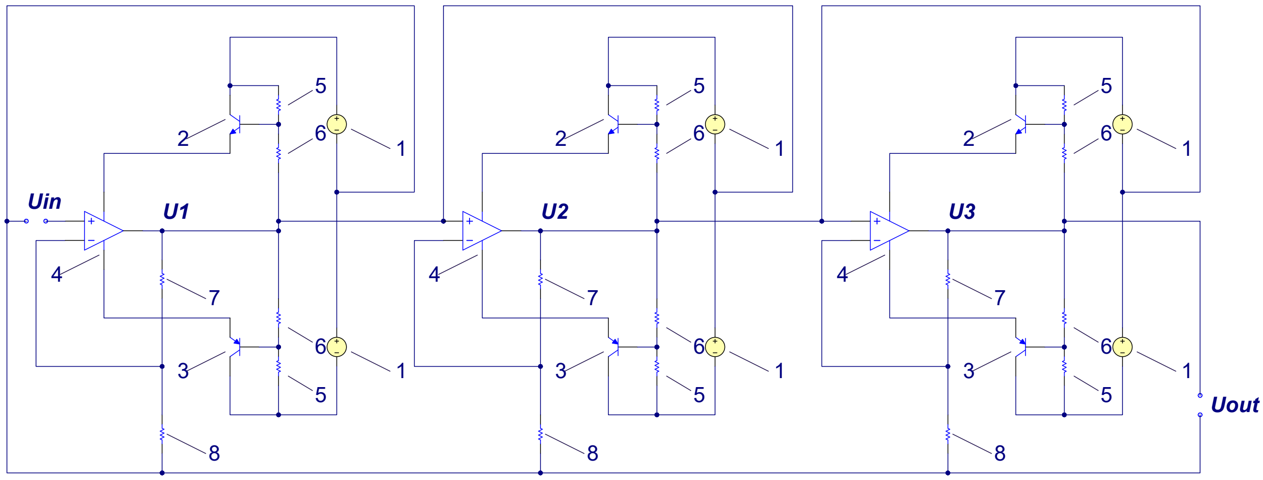

Figure 5. High-voltage non-inverting broadband cascade amplifier
Source: created by the authors

This amplifier consisted of three stages, with each stage containing two power sources (1), an operational amplifier (4), and a transistor repeater based on a bipolar NPN transistor (2) and a PNP transistor (3). In addition, two dividers were present in each stage: one for setting the operating voltage, which consisted of resistors (5) and (6), and the other for adjusting the signal gain, which included resistors (7) and (8) (Jung *et al*., 2020; Roongmuanpha *et al*., 2021). The technical result of the claimed solution is an extension of the operating range of the input voltage and a reduction in the error of the output signal. And due to independent feedback, the sensitivity of the feedback link to parasitic characteristics of elements and structures decreases and the influence of other working stages (Bai *et al*., 2021; Lee *et al*., 2021). The proposed combination of features that determines the essence of the utility model was not known from previous technical solutions, so this utility model met the criterion of innovation. The proposed high-voltage non-inverting broadband cascade amplifier can be implemented according to the scheme shown in Figure 5.

The utility model was illustrated by an example of its application. This model was a non-inverting broadband cascade amplifier consisting of separate independent stages connected in series to extend the operating range of the input voltage. Each stage was made in the form of a separate operational amplifier, tuned according to a non-inverting feedback circuit, with independent power supply, a transistor repeater and a voltage divider of the operating power point.

The input voltage applied to each stage was amplified by Kn times, which was provided by a voltage divider of the operating power point on resistors 5 and 6. Additional transistor stages helped to double the operating range of the output voltage by shifting the operating power point. A floating supply voltage shaper for each stage was implemented using the following components: 1, 2, 3, 5, 6. The supply voltage sources 1 were connected in series, creating a bipolar supply voltage with a nominal value equal to twice the maximum value of the operating voltage of the operational amplifier 4. Input signal (U_{in}) received on a non-inverting input of operational amplifier 4, output signal on the first stage (U_{out1}) was formed according to equation (8).

High-voltage non-inverting broadband cascade amplifier: utility model patent (2023) was capable of implementation in industrial production. Thus, this technical solution met the criterion of industrial suitability and could be protected by a patent of Ukraine for a utility model. In the field of high-voltage generation by broadband amplifiers, the use of low-voltage amplifier stages together with the voltage doubling method is considered. The main problem is that operational amplifiers (OAs) with better frequency characteristics and higher gain rates usually have a low supply voltage. One possible solution is to use high-speed amplifiers such as the Apex PA98 instead of the Apex PA94. Apex PA98 amplifiers have a wider bandwidth and higher build-up rate compared to the PA94, but their operating voltage is half that. Using the voltage doubling method described in the patent, it was possible to expand the frequency band to 150 kHz when generating a 1,000 V signal with a moderate deviation of 680 ppm. This method ensured high accuracy and stability when working with high voltages over a wide frequency range.

The voltage doubling method consists of cascading multiple amplifiers with independent power supplies, which allows doubling the output voltage. Each stage contains an operational amplifier and feedback links that ensure accurate signal processing. For stable and efficient operation, operational amplifiers are powered by transistor repeaters that provide the required power levels. By carefully selecting the gain and supply voltage, the amplifier system achieves an extended output voltage range. Existing methods of high voltage generation often have certain limitations. For example, transformer converters provide stable operation, but do not support a wide frequency band and constant voltage signals. Cascade amplifiers based on operational amplifiers and optocouplers can generate constant voltage signals, but have low accuracy and a narrow frequency band. Y.M. Tuz (2012) described methods for configuring operational amplifier stages for generating high voltage over a wide frequency range, but while maintaining the accuracy and speed of signal rise.

The new approach under consideration allows using high-speed amplifiers with low supply voltage to generate high voltage in a wide frequency band. This ensures high accuracy and stability of the output signal. For example, the use of Apex PA98 amplifiers and the voltage doubling method allows reaching 1,000 V in the band up to 150 kHz with a deviation of 680 ppm. This significantly improves the frequency response and signal growth rate compared to conventional approaches (Dovhal & Tuz, 2024). A review of existing solutions has shown that the new approach using low-voltage amplifier stages and the voltage doubling method has significant advantages. It allows achieving high accuracy and stability when generating high voltage over a wide frequency range. This makes it promising for further research and implementation in the metrological certification and calibration of thermoelectric transducers.

Cascade connection of amplifiers is an effective method of extending the range of operating voltages and frequencies of amplifiers. In cascade circuits, each amplifier amplifies the signal coming from the previous stage, thereby increasing the total output voltage of the system. However, cascading also brings a number of problems, among which the main ones are signal stability and error control. In cascade circuits, the main task is to ensure stable gain at each stage to avoid cumulative signal distortion. The amplifiers in the stage must be optimally tuned so that each subsequent amplifier receives a signal with the required voltage level and minimal distortion. This requires careful selection of the feedback and resistance parameters of the resistors used to adjust the signal gain.

DISCUSSION

A high-voltage operational amplifier PA94 was used in the study, which allowed achieving stability and high accuracy of the output signal, which is critical for ensuring reliable operation of electronic systems under variable load conditions. This solution has significantly improved the reliability of electronic devices in industrial and scientific systems where load fluctuations often occur. Stability of characteristics in such conditions is a crucial factor for ensuring smooth operation of systems.

Cascade coupling of amplifiers proved to be an effective method for extending the frequency range and increasing the operating voltage, which contributed to improving the efficiency and functionality of amplifiers in systems that require a wide frequency range and high voltage. This ensured reliable operation in difficult operating conditions. Comparison with the study by J. Chen *et al*. (2022), where thin-film transistor-based amplifiers focus on compactness and energy efficiency, have demonstrated good results for high voltage industrial applications where stability under variable loads is important. An innovative approach to minimising errors through the additive error correction scheme has significantly improved the quality of the output signal and reduced its distortion (Hula & Hryha, 2024). This ensured the stability of the system even under variable operating conditions, which is especially useful for high-precision systems such as medical devices or process control systems. Reducing errors helped to avoid possible failures in operation, which is important for modern technologies (Smailov *et al*., 2023).

Compared to the study by M.M. Tarar *et al*. (2024), who developed a multi-stage distributed amplifier (LC-CMS-DA) based on 65 nm CMOS technology, demonstrated higher stability indicators at high voltages. Amplifier by M.M. Tarar *et al*. (2024) provided a peak gain of 21.5 DB over 50 GHz bandwidth, which is an important indicator for high-frequency systems. However, this approach was not as effective for tasks that required high operating voltage and signal stability under variable loads. Specialised software was used to achieve accurate device operation parameters, which significantly improved the efficiency and reliability of the amplifiers. Optimisation of operating parameters under high voltage and variable loads provided better results compared to other approaches.

The study by Z. Wang *et al*. (2023), which focused on broadband millimetre wave amplifiers for 5G and satellite communications, demonstrated high-frequency performance with a frequency range of 25.8-36.9 GHz. This made the amplifier suitable for high-frequency communication systems. However, unlike the solution, which focused on stability at high voltages, approach by Z. Wang *et al*. (2023) was aimed at the narrow industry of high-frequency applications and failed to provide the same efficiency in high-voltage operations. One of the technical innovations in the study by Z. Wang *et al*. (2023) was the possibility to use a magnetically coupled resonator network for output matching, which provided high performance when working with large and small signals. This made the amplifier effective for modern communication systems such as 5G. However, its performance in industrial applications with high operating voltage was not as high, as the focus on signal stability under variable load and high voltage is an important aspect for industrial systems.

The research involved the development of cascade power amplifiers with an emphasis on the stability and accuracy of the output signal under variable load conditions. The use of a high-voltage operational amplifier ensured not only stable operation of electronic systems, but also increased efficiency in industrial conditions (Bondarenko *et al*., 2019). Compared to the study by C. Zhao *et al*. (2022), which focuses on a broadband CMOS low-noise amplifier (LNA) with multiple resonant frequencies, the current study focused on achieving high stability under different loading conditions. C. Zhao *et al*. (2022) discussed the development of an LNA that uses a common source (CS) topology and inductive degeneration to expand the bandwidth. While both studies highlight the importance of working with broadband amplifiers, the current study focused on stability and high output power under variable loads. The cascade amplifier connection technology used in the current study provided an extension of the frequency range and an increase in the operating voltage. C. Zhao *et al*. (2022) focused on achieving multiple resonant frequencies to reduce noise, which has improved the overall performance of the amplifier, but narrow bandwidth is still a limitation. In the above study, cascade connection technology not only improved performance over a wide frequency range, but also ensured stable operation of the system under high loads, making this solution more suitable for high-voltage industrial applications.

The development of cascade amplifiers also considered the technology of additive error correction, which minimised distortion and maintained signal stability (Bondarenko *et al*., 2018). While the study by C. Zhao *et al*. (2022) demonstrates the application of inductive degeneration to generate multiple resonant frequencies and improve the noise characteristics of an amplifier, this study focused on signal stability under high voltage and wide bandwidth conditions. This solution was important for applications where high reliability is required when working with unstable loads. Also worth noting is the comparison with study by S.R. Boroujeni *et al*. (2020), which refers to a broadband CMOS low-noise amplifier (LNA) using a common source topology with inductive degeneration. In this study, it was proposed to use a shunt resonator to improve the bandwidth of the amplifier by generating multiple resonant frequencies. Both approaches demonstrate advances in the development of wide-band amplifiers, but the main emphasis remains different. In the study by S.R. Boroujeni *et al*. (2020), the emphasis is placed on noise characteristics and bandwidth, while the current study emphasises the need for stable operation of power amplifiers under high voltage and alternating load conditions. The use of software to optimise the operation parameters of devices helped to determine the optimal conditions for ensuring the efficiency of amplifiers. This made it possible to achieve stable performance under variable load conditions. Compared to the study by S.R. Boroujeni *et al*. (2020), where the main goal was to improve bandwidth and reduce noise through the use of an innovative topology, the current study focused on stability when operating at high voltages, which is important for tasks where accuracy and reliability are critical.

Overall, the successful integration of state-of-the-art materials and technologies to create high-voltage amplifiers with improved stability and accuracy characteristics was demonstrated. Compared to other studies, such by S.R. Boroujeni *et al*. (2020) and C. Zhao *et al*. (2022), which focused on improving noise performance and bandwidth in low- voltage systems, this study focused on ensuring stable operation under high voltages and variable loads, making it more suitable for industrial and scientific applications where high voltage and stability are key requirements. L. Xu *et al*. (2020) developed a high-voltage operational amplifier based on the general principles of operational amplifiers, particularly for applications with piezoelectric actuators. The main innovation is the use of the amplifier as a non-inverting one, considering the effect of piezoelectric elements on the circuit. In addition, the simplicity of the design and feedback principles ensured low noise, compactness, and the possibility of implementation using discrete components (Bagatskyi *et al*., 2023). In an experiment focused on precise positioning, it was shown that the amplifier works in accordance with theoretical expectations.

The study of cascade power amplifiers is also focused on high-voltage operation, but the emphasis is on the stability of the output signal under variable loads. While research on a high-voltage operational amplifier has focused on providing low noise and compactness, achieving stability at high voltages and a wide frequency range has been a key aspect here. Since research on operational amplifiers uses piezoelectric actuators for precise positioning, this increases its potential in areas such as precision mechanics and control. Overall, the study showed successful integration of modern materials and methods to achieve high stability and accuracy of the output signal. Compared to other studies, this solution has shown advantages for applications that require stability and accuracy under variable loads and high voltages. The results of the study have significant potential for further use in industry and science, where the accuracy, stability and reliability of electronic systems are important. This approach opens up new opportunities for improving technologies in the field of high-voltage electronics and contributes to the further development of the modern industry.

CONCLUSIONS

The use of high-voltage operational amplifiers PA94 helped to ensure high stability of the output signal even under variable loads. The amplifiers have demonstrated reliability and versatility, which makes them promising for use in various industries. The high technical characteristics of the PA94, such as the ability to work with capacitive loads and transmit direct and pulsed currents, allow expanding the scope of their application. Cascade coupling of multiple amplifiers has become a key methodological approach in the study. It helped to significantly expand the frequency range and operating voltage range of amplifiers. This method has proven to be particularly effective in achieving high output voltage values while maintaining high signal accuracy, which is important for many industrial applications.

The use of an additive error correction scheme minimised distortion of the output signal and improved its quality. This scheme helped to maintain the stability of the amplifiers even in difficult conditions, which increased the reliability of the developed system. Minimising errors is critical to ensuring the accuracy and efficiency of amplifiers in industrial and scientific research. Modelling and computational studies have played a crucial role in the process of optimising the amplifier design. The use of specialised software allowed performing accurate calculations, which helped to find the optimal parameters of the devices and their design features. This contributed to improving the efficiency and reliability of the developed systems. The results of the study showed that the use of modern materials and methods makes it possible to create high-voltage amplifiers with improved technical characteristics that meet the requirements of modern industry and science. These amplifiers have the potential for further improvement and development, which opens up new prospects for their application in various industries.

One of the main limitations of this study was its focus on operational amplifiers PA94, which may limit the application of the results obtained for other types of amplifiers or technologies. Although the use of a cascade connection of amplifiers helped to extend the frequency range and operating voltage interval, this method did not always provide efficient operation at very high frequencies due to the internal characteristics of the PA94. In addition, the complexity of the design of amplifiers due to the use of a cascade connection and an additive error correction scheme complicated their production and maintenance. High-voltage operation also caused problems with heat dissipation, which affected the stability and reliability of the amplifiers. In addition, the simulation results, although useful, did not always fully correspond to the actual operating conditions, which could lead to deviations in performance.

To further improve these amplifiers, it would be advisable to conduct additional experimental studies under conditions as close to real conditions as possible to test the accuracy of the simulation results. In addition, it would be worth considering simplifying the design of amplifiers without reducing their performance, which could reduce production costs and increase their reliability. It is important to pay attention to improving heat dissipation systems to ensure stable operation of high-voltage amplifiers. To further expand the frequency range of amplifiers, the use of new materials or technologies may be considered. It would also be useful to explore the possibility of using similar methods for other types of high-voltage amplifiers, which could allow scaling the results to other areas.

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CONFLICT OF INTEREST

None.

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Методи формування високої напруги шляхом каскадування підсилювачів

Анотація. Метою даного дослідження було створення нової моделі високовольтного вимірювального підсилювача, яка б включала кілька каскадів операційних підсилювачів для збільшення діапазону робочої напруги шляхом послідовного «віртуального» підключення вихідних напруг кожного з каскадів. Методологія дослідження включала використання каскадного з'єднання підсилювачів, схеми адитивної корекції похибки, а також моделювання та розрахункових досліджень для оптимізації конструкції високовольтних операційних підсилювачів. Результати дослідження показали, що використання високовольтних операційних підсилювачів PA94 забезпечує високу стабільність і точність вихідного сигналу навіть при змінних навантаженнях. Каскадне з'єднання підсилювачів дозволило розширити частотний діапазон та збільшити робочу напругу, що підвищило ефективність їх роботи. Застосування схеми адитивної корекції похибки значно зменшило спотворення сигналу, підвищивши його якість. Моделювання та розрахункові дослідження оптимізували конструкцію підсилювачів, що сприяло досягненню високих технічних характеристик. Завдяки поєднанню цих методів було створено надійну систему з поліпшеними параметрами. Підсилювачі показали перспективність для широкого спектру промислових і наукових застосувань. Вони здатні працювати в складних умовах із високою точністю. Дослідження підтвердило важливість інтеграції сучасних технологій у розвиток електронних систем. Розрахункові дослідження нової моделі високовольтного вимірювального підсилювача демонструють, що застосування кількох каскадів операційних підсилювачів разом зі схемою адитивної корекції похибок дозволяє значно розширити частотний діапазон підсилювача та збільшити робочий інтервал напруг, що призводить до покращення якості вимірювань

Ключові слова: високовольтний вимірювальний пристрій; опір; діапазон; калібратор; електроніка

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Mathematical modelling of solar power converters

Abstract. The study was conducted to develop a mathematical model of photovoltaic systems using artificial neural networks. A mathematical model of the photovoltaic system was established, a simulation process was implemented considering key parameters, and a maximum power point tracking method was applied to improve the efficiency of the system. In this research, a mathematical model of photovoltaic system based on artificial neural networks was developed and tested to improve the efficiency of solar panels. The model showed high accuracy in predicting the maximum power point under varying environmental conditions such as illumination and temperature. Analysis of the data demonstrated that the use of neural networks for maximum power point tracking significantly reduces energy losses compared to traditional tracking methods. Experimental results confirmed that the proposed approach provides more stable and accurate detection of the maximum power point in real time. The findings showed that the implementation of such a system could significantly improve the overall performance of PV plants, especially under erratic solar conditions, making it promising for applications in different climatic zones. In addition, the model was shown to be robust to changes in input data parameters, making

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it adaptive to different types of solar panels and operating conditions. It was also found that the neural network-based system reduces PV plant operation and maintenance costs by minimizing the need for manual calibration and monitoring. The resulting model will improve the accuracy and efficiency of maximum power tracking of solar panels under varying environmental conditions

Keywords: maximum power; illumination; temperature; prediction; neural networks

INTRODUCTION

Mathematical modelling of solar converters occupies an important place in improving their efficiency and reliability. With the increasing interest in renewable energy sources such as solar panels, more and more attention is being paid to the development of methods for optimizing their performance. Current approaches based on artificial neural networks allow for improved prediction and control, minimizing energy losses under changing environmental conditions. The development of mathematical models capable of accurately tracking the maximum power point (MPP) in real time is an important step towards increasing the performance of solar converters and their adaptability to different climatic conditions. These models help to ensure more efficient utilization of solar energy, which in turn helps to improve the resilience of the systems and makes them more attractive for deployment in different regions. Given current energy trends and challenges, integrating such models into the operation of solar plants can significantly reduce maintenance costs and improve overall performance, making research in this area particularly relevant.

The problem of improving the efficiency of solar power converters remains relevant in light of global climate change and the need for sustainable energy sources. C.G. Villegas-Mier *et al.* (2021) investigated the use of artificial neural networks to improve the efficiency of solar panels. In their work, the authors demonstrated that such networks significantly improve MPP prediction accuracy, which in turn can lead to more efficient utilization of solar energy under different conditions. A.M. Soomar *et al.* (2022) investigated methods for optimizing the performance of photovoltaic systems under varying solar activity. From their study, it was evident that adaptive models outperform conventional approaches by providing higher efficiency under variable environmental factors. K. Fatima *et al.* (2022) emphasized the integration of intelligent systems into MPP tracking. This solution helps to reduce energy losses and improve the overall performance of solar installations, which is important for reliability. C.D. Hewitt *et al.* (2021) proposed the development of adaptive models that take into account the climatic characteristics of different regions. They point out that this approach is important to improve the efficiency of solar systems, ensuring that they perform optimally in different climatic conditions. A. Elnozahy *et al.* (2021) discussed improving the stability of solar systems based on neural networks. The results of their study show that process automation can achieve more reliable operation of solar installations and minimize the risks of failures.

A. Mellit & S. Kalogirou (2021) analysed the impact of intelligent solutions on reducing operating costs. The paper demonstrated that minimizing manual calibration greatly simplifies the maintenance of solar plants and reduces their operating costs. K.B.M. Kiran *et al.* (2021) examined the robustness of models to changes in input parameters. In the study, the authors concluded that such models are more effective under a variety of operating conditions, making them promising for future use. M.A. Mari *et al.* (2021) emphasized the long-term reliability of the proposed solutions. Their research opened new perspectives for future research in the renewable energy field, allowing the improvement of solar energy technologies. P. Sharma *et al*. (2021) considered the possibility of integrating the new models into global energy networks. The authors highlighted that such integration could significantly expand the application horizons of solar technologies and increase their international availability. Nevertheless, there remain gaps in research on the impact of long-term operation on the stability of the models, as well as the need to better analyse the interaction of new technologies with existing energy systems. In addition, research does not fully cover the integration of renewable energy into existing energy infrastructure, which requires further attention. The aim of the study was to develop a mathematical model using neural networks to optimize the performance of solar panels under changing conditions.

The objectives of the study were:

1. Analysing the role of mathematical modelling in optimizing the performance of solar converters.

2. Reviewing various approaches to the use of artificial neural networks in the context of predicting the maximum power output of solar panels.

3. Evaluating the results of implementing these models in real-life operating conditions and their impact on the overall performance of the systems.

MATERIALS AND METHODS

In this study, the equivalent external characteristics' method was used to mathematically model the operation of a photovoltaic system. The main objective of this approach was to create a mathematical model of a high-power photovoltaic system that takes into account the key parameters of a real power source such as short circuit current, no-load voltage, maximum current, operating point voltage, temperature and illumination intensity, and physical properties of the solar cells. The modelling was carried out in MATLAB/SIMULINK environment, where the model parameters were carefully calculated to describe the operation of the photovoltaic power source. An important step in the process was the simplification of the complex mathematical equations detailing the operation of the photovoltaic cells, allowing the formulas to be optimized to accurately calculate current and voltage in response to light and temperature conditions.

One of the key steps was the use of a mathematical model including an equivalent circuit of the photovoltaic system based on an equivalent circuit consisting of a current source, diodes, and resistors connected in series and parallel. This model was used to calculate the dependence of the system current and power on temperature and illumination level, which is important for evaluating its performance (Fig. 1).

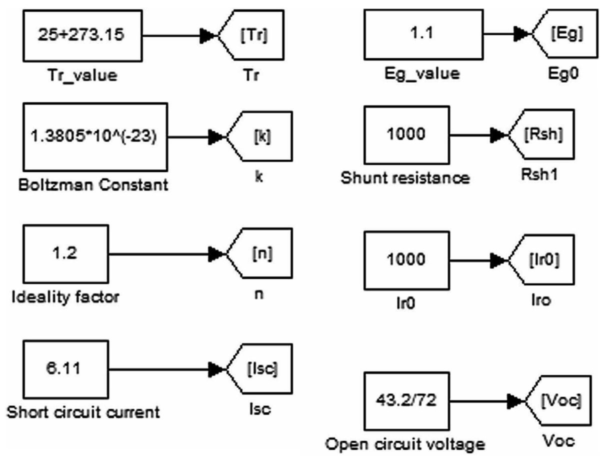

Figure 1. Parameters set before running the model

Note: Tr – reference temperature (298.15 K), n – diode ideological factor (1.2), k – Boltzmann constant, q – elementary charge, Isc – short circuit current under standard test conditions (STC), Eg0 – silicon forbidden bandwidth, Rs – series resistance, Rsh – shunt resistance

Source: created by the authors

As part of the study, a simplified version of the equations describing the operation of the photovoltaic system was created, making it easier to account for the effects of temperature and changes in solar radiation intensity on its operation. The main focus was on the equations for calculating the short-circuit current, no-load voltage, and maximum current and voltage at the operating point of the system. In order to obtain accurate results, a simulation modelling process of the solar module was developed based on the above equations. The process was carried out in a step-by-step manner where each circuit component including the photocurrent source, and the reverse saturation current of the module was modelled separately. Separate circuits were also created to simulate each equation at each stage of the calculation, which provided higher simulation accuracy and facilitated further analysis of the performance of the photovoltaic system.

In the investigated photovoltaic system, six modules were used, each module comprising six solar cells connected in series. This configuration was chosen to achieve the required power level. To improve the overall efficiency of the system, maximum power point tracking was implemented, which significantly improved its performance under varying light and temperature conditions. The use of modern technology in the simulation process will ensure high reliability and accuracy of the results, which will optimize the performance of photovoltaic systems and improve their efficiency in real-world conditions.

In this study, neural networks were used to optimize the mathematical modelling of photovoltaic systems. Specifically, artificial neural networks were applied and trained on historical data to predict power output as a function of temperature and lighting intensity. This approach allowed the identification of non-linear dependencies that are difficult to describe using traditional methods. Neural networks were also used to identify deviations in system performance, which increased the accuracy of the modelling and enabled effective monitoring and control of the photovoltaic plants, improving their overall performance.

RESULTS

Mathematical model of photovoltaic systems

Photovoltaic cells are the heart of solar cells. Their operation is based on the principle of converting light energy into electrical energy by means of a PN junction. The equivalent circuit of a photovoltaic cell includes photocurrent, which depends on the light intensity, and diode current, which is determined by the voltage on the cell. The external characteristic of a photocell describes the voltage dependence of the output current and allows calculating its parameters (1):

$$I = I_{ph} - I_{sat}\left(\exp\left(\frac{q(U+IR_S)}{Ak\theta}\right) - 1\right) - \frac{U+IR_S}{R_{sh}}. \tag{1}$$

The parameters A, k, q, R_s and R_{sh} are included in the equation describing the solar cell voltampere characteristic. The ideality factor A characterizes the quality of the p-n junction, while the resistances Rs and Rsh account for ohmic losses in the base and emitter layers, respectively. To develop a mathematical model of a high-power photovoltaic system, the method of equivalence of external characteristics is applied. This method is based on the comparison of real solar cell characteristics, such as short-circuit current, no-load voltage and maximum power, with the parameters of a simplified electrical circuit (Katche *et al.*, 2023). The aim of the method is to create a universal model that allows simulating the behaviour of a photovoltaic system, regardless of the number and type of elements used. The mathematical model is created based on (Fig. 2).

Model description:

i. the term $(U+IR_s)/R_{sh}$ in equation (1) is much smaller than the photogenerated current and is ignored;

ii. under normal conditions, the resistance R_s is less than the forward conduction resistance of the diode, which allows us to ignore the coefficient $IR_s/Ak\theta$. In this case, I_{ph} can be equated to I_{sc}, which leads to a simplification of equation (1) to the following form (2):

$$I = I_{ph} - I_{sat}\left(\exp\left(\frac{IR_S}{Ak\theta}\right) - 1\right). \quad (2)$$

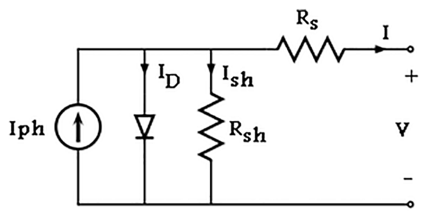

Figure 2. Schematic diagram showing the process of converting light energy into electrical energy in a solar cell

Note: I_{ph} – photocurrent current; I_d – diode current; I_{sh} – bypass current; R_{sh} – shunt resistor; R_s – series resistor; I – current, v – voltage

Source: created by the authors

If $C_1 = I_{sat}/I_{sc}$ and $C_2 = AR\theta/q$, then the above formula is expressed as (3):

$$I = I_{sc}(1 - C_1\left(\exp\left(\frac{U}{C_2 U_{oc}}\right) - 1\right)), \quad (3)$$

where U is the voltage at the terminals of the solar cell; U_{oc} is the open circuit voltage.

To find C_1 and C_2, the following two conditions are used:

i. in the open circuit state $I = 1$, $U = U_{oc}$;

ii. at the point of maximum power $U = U_m$, $I = I_m$.

When substituted into equation (ii), the authors obtain (4, 5):

$$C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) \exp\left(-\frac{U_m}{C_2 U_{oc}}\right), \quad (4)$$

where U_m is the maximum voltage.

$$C_2 = \left(\frac{U_m}{U_{oc} - 1}\right)(1n\left(1 - \frac{I_m}{I_{sc}}\right))^{-1}. \quad (5)$$

Based on this, taking into account the change in temperature $\Delta\theta = \theta - \theta_{ref}$ and the change in light intensity $\Delta S = S/S_{ref} - 1$, it turns out (6-9):

$$I'_{sc} = I_{sc}(1 + \Delta S)(1 + a \times \Delta\theta), \quad (6)$$

$$U'oc = Uoc(1 - c \times \Delta\theta \ln(e + b \times \Delta S), \quad (7)$$

$$I'm = Im(1 + \Delta S)(1 + a \times \Delta\theta), \quad (8)$$

$$U'm = Um(1 - c \times \Delta\theta)\ln(e + b \times \Delta S), \quad (9)$$

where θ_{ref} = 25°C and S_{ref} = 1 kW/m^2 – ambient temperature and luminous intensity under standard conditions, respectively; a = 0.0025°C^{-1} – current temperature coefficient under standard conditions; b = 0.5 – constant; c = 0.00288°C^{-1} – temperature coefficient of voltage under standard conditions; e – base of natural logarithm.

As input data for the model, the main technical characteristics of the solar panel are used. Based on mathematical equations (3-8), a simulation model is created in MATLAB/SIMULINK environment, where current and power are output quantities depending on temperature and illumination level. The model is an electrical circuit including diodes, current source and resistors and allows simulating the operation of the solar module under different conditions (Fig. 3).

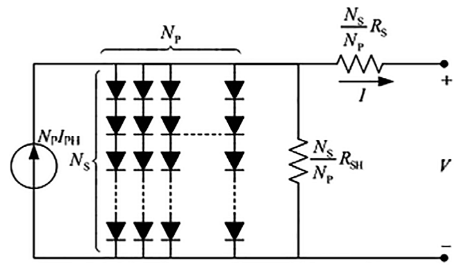

Figure 3. Electrical diagram corresponding to the actual behavior of a photovoltaic cell

Source: created by the authors

The mathematical model describing the dependence of current on voltage in a solar cell is as follows. The photocurrent of the module, i.e., the current generated by light, is (10):

$$I_{ph} = [I_{sc} + K_i(T - 298)] \times Ir/1000. \quad (10)$$

The dependence of the current on the voltage in a solar cell is described by the following equation. The current created by light is (11):

$$I_{rs} = I_{sc}/[\exp(qV_{OC}/N_S knT) - 1]. \quad (11)$$

Maximum module current (12):

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^2 exp\left[\frac{q \times E_{go}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right]. \quad (12)$$

Current generated by solar panel (13-15):

$$I = N_p \times I_{ph} - N_p \times I_0 \times \left[\exp\left(\frac{\frac{V}{N_s} + I \times \frac{R_S}{N_P}}{n \times V_t}\right) - 1\right] - I_{sh}, \quad (13)$$

$$V_t = \frac{k \times T}{q}, \quad (14)$$

$$I_{sh} = \frac{V \times \frac{N_P}{N_S} + I \times R_S}{R_{sh}}, \quad (15)$$

where N_p is the number of panels connected in parallel; R_s is the resistance in the circuit; R_{sh} is the additional resistance; V_t is the temperature-dependent voltage.

The photocurrent given by equation (10) was numerically simulated and presented graphically in Figure 4 (at standard illumination intensity).

The dependence of the reverse current on various parameters is described by equation (11). The results of the numerical solution of this equation are presented in Figure 5.

The saturation current of the module is presented in equation (12) and modelled in Figure 6.

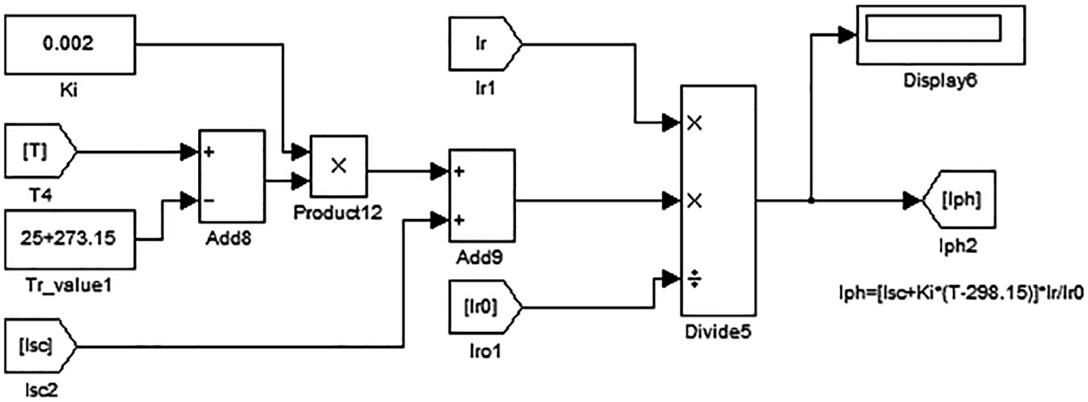

Figure 4. Simulated circuit for equation (10)

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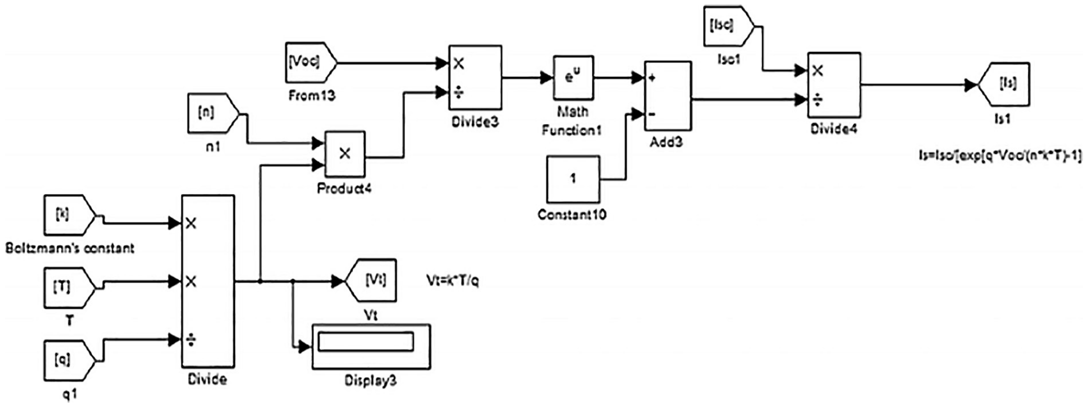

Figure 5. Simulated circuit for equations (11-14)

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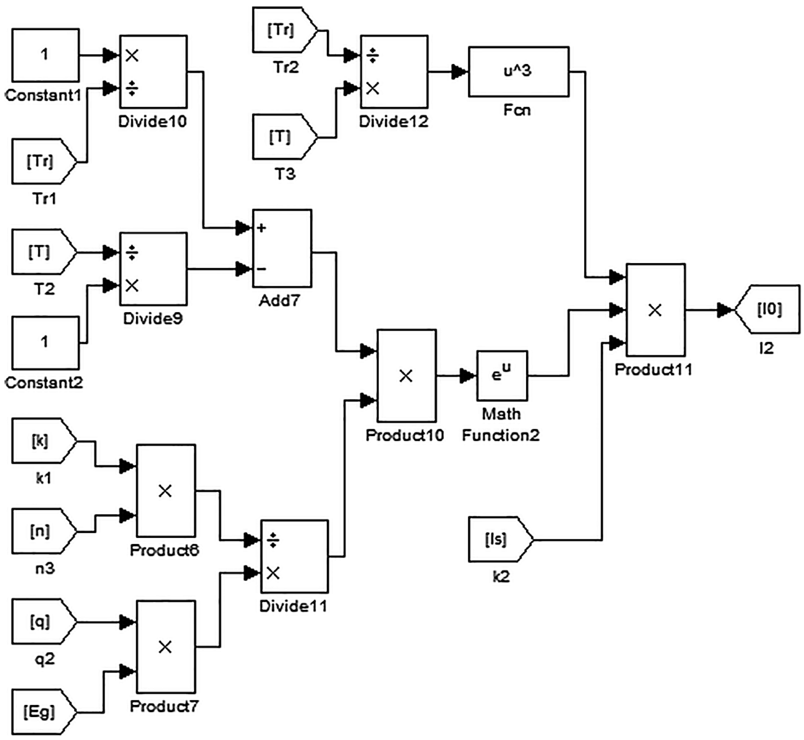

Figure 6. Simulated circuit for equation (12)

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It was simulated circuits for equation (15) (Fig. 7) and equation (13) (Fig. 8).

The simulation process of the solar module is shown in Figures 3-8. The photovoltaic system consisting of 6 modules with 6 elements connected in series was simulated and shown in Figure 9. Simulation can be used to evaluate the performance of photovoltaic modules and arrays under various operating conditions. Changes in solar radiation, temperature, and partial shading have a significant impact on the system output.

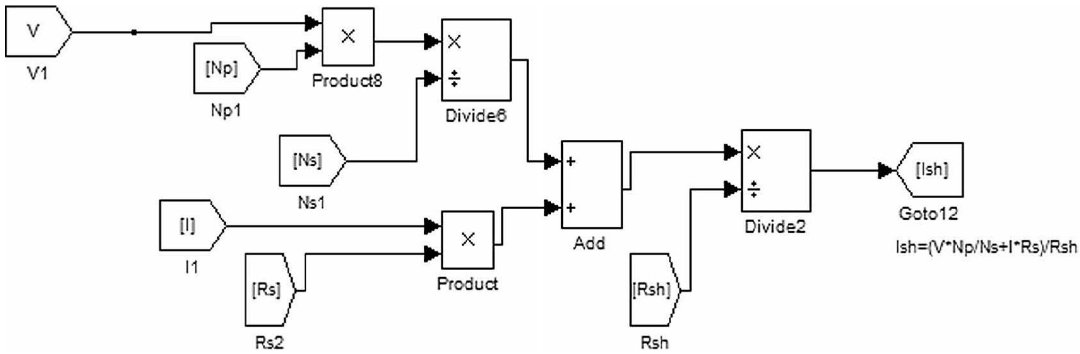

Figure 7. Simulated circuit for equation (15)

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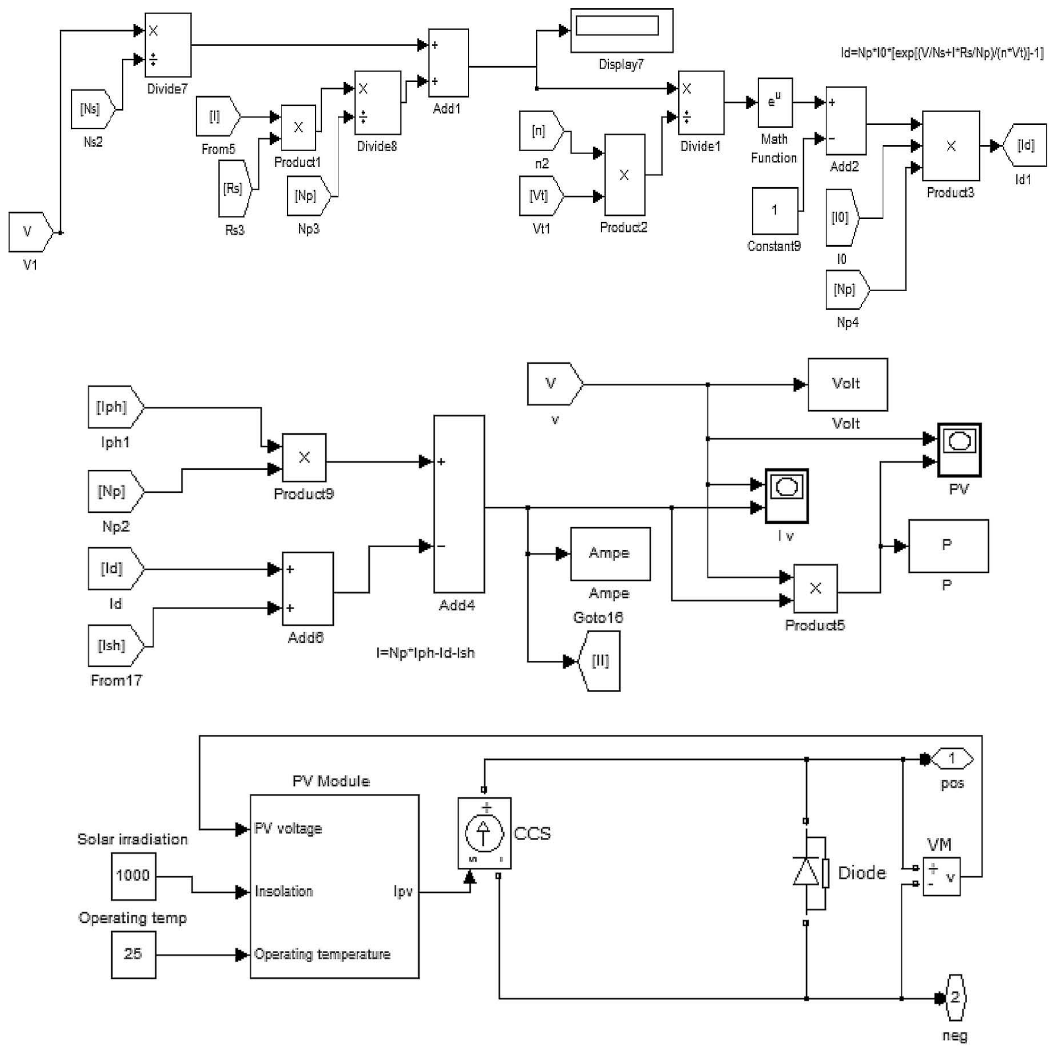
a



b

Figure 8. Modelling of a photovoltaic system

Note: a) block diagram corresponding to equation (13); b) simulation model of solar power plant

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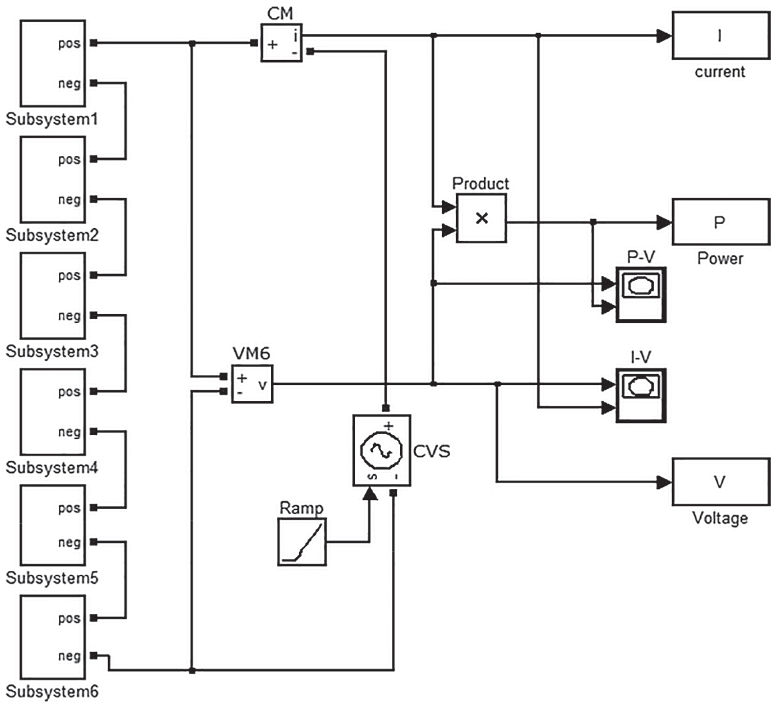

Figure 9. Model simulating the operation of a solar battery

Source: created by the authors

Optimization algorithms: MPPT in solar panels

Maximum power point tracking (MPPT) algorithms are used to improve the efficiency of solar energy conversion. Figure 10 shows a block diagram of a solar generator including a DC-DC converter with an MPPT algorithm.

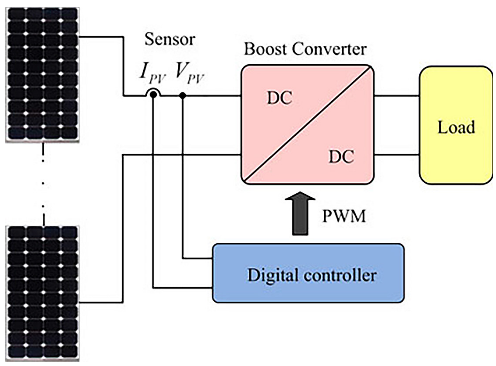

Figure 10. Structural diagram of the photovoltaic installation

Note: I_{pv} – current generated by solar panels (A); V_{pv} – voltage generated by solar panels (V); PWM – pulse width modulation – a method of power control in electronic devices by changing the width of DC pulses

Source: created by the authors

Boost converter, controlled by the MPPT algorithm, ensures maximum efficiency of the solar photovoltaic system. MPPT, in turn, uses data on solar radiation, temperature and other parameters to optimize the output power. Artificial intelligence allows increasing the speed and accuracy of the MPPT algorithm (Sarang *et al.*, 2024). The structural diagram of the system is shown in Figure 11.

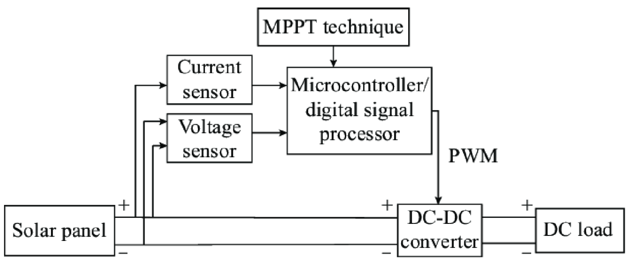

Figure 11. Scheme of the solar energy optimization algorithm

Note: PWM – pulse width modulation – a method of controlling power in electronic devices by changing the width of DC pulses

Source: created by the authors

Designing a traditional control system requires mathematical modeling, since the developer needs to create a mathematical model of the control object before monitoring it. Numerous artificial intelligence algorithms demonstrate satisfactory results, among which the algorithms of artificial neural networks (ANN, Artificial Neural Networks (ANN). In general, an ANN is a computational model that imitates a biological neural network (Pulvermüller *et al.*, 2021). In such a model, a neuron is a processor that first linearly weights the input data, then calculates the sum using a nonlinear function called the activation function (activation function, AF), and finally sends the results to the next neurons. The model of a regular neuron (Figure 12) is given by the relation:

$$z = \sum_{m=1}^{M} W_m x_m + \alpha, \tag{16}$$

where z is the final variable, which is the sum of the products, M is the total number of elements in the sum, W_m is the weighting coefficient for the mmm -th element, x_m is the value of the mmm-th element, which affects the final value, α is a constant or free term added to the sum.

Figure 12 shows a three-layer neural network, where the input layer receives a vector of features characterizing the solar battery (IPV and VPV), the hidden layer performs a nonlinear transformation of the input data, and the output layer generates a vector of output values.

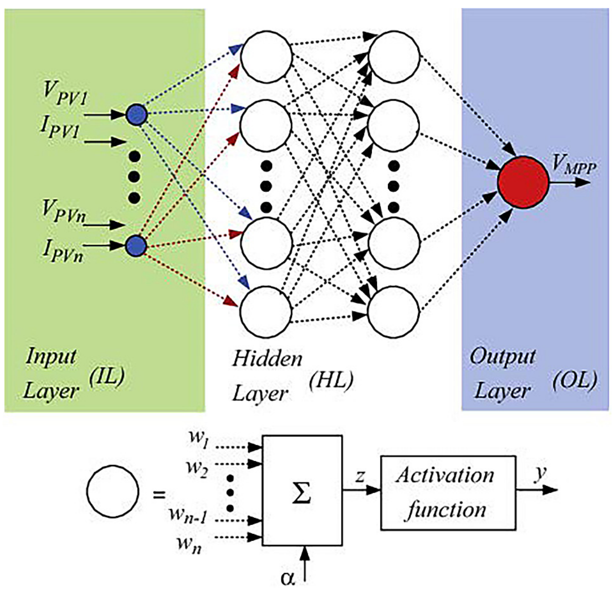

Figure 12. Neural network for solar panels

Note: V_{pv1}, V_{pvn} – input variables. V are the voltages measured on the photovoltaic panels (PV). Index "n" indicates the number of such panels or voltage sources used as input to the neural network, I_{pv1}, I_{pvn} – the corresponding currents for the same photovoltaic panels. These pairs of data (voltage and current) represent the state of each panel, Input Layer (IL) is the input layer of the neural network, Hidden Layer (HL) is the hidden layer of the neural network, Output Layer (OL) is the output layer consisting of one neuron that produces the predicted value – the voltage at the maximum power point, VMPP is the target variable denoting the voltage of maximum power point (Maximum Power Point), at which the photovoltaic system generates maximum electrical power

Source: created by the authors

ANN is used to train and test the nonlinear relationship between IV and PV characteristics. Using input data such as current, voltage, solar radiation, temperature and metrology data, ANN extracts these parameters and continuously learns to optimize the operation of the solar energy system to achieve maximum power. To implement the maximum power point tracking (MPPT) algorithm based on artificial neural network, a supervised learning method is used (Fig. 13). Solar radiation and temperature data are used as training data (Abouzeid *et al.*, 2024). A trained neural network controls a DC/DC converter to obtain maximum power from a photovoltaic array.

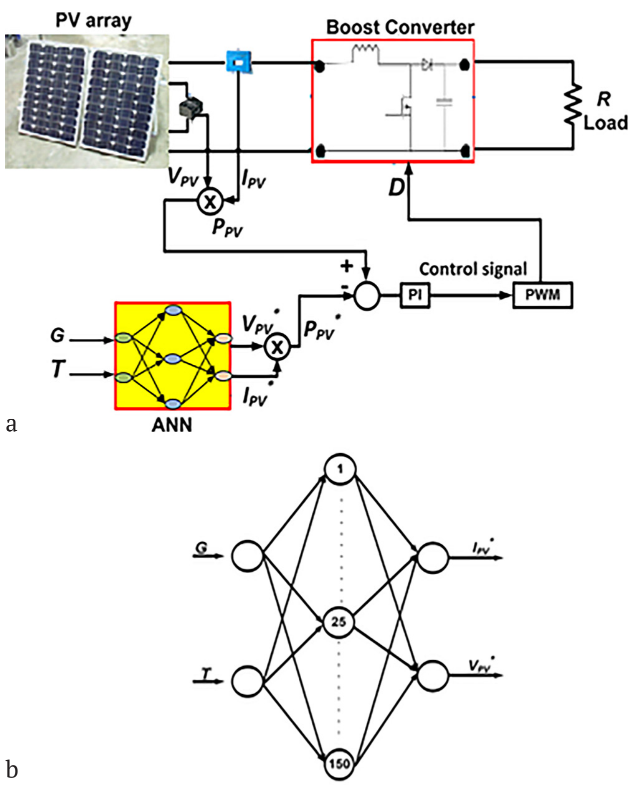

Figure 13. Modelling the operation of a photovoltaic system using a neural network

Note: a) system diagram; b) neural network structure

Source: created by the authors

Photovoltaic inverters are classified into two types (Salem *et al.*, 2024): stand-alone inverters for isolated systems (SAPV) and grid-connected inverters for systems connected to the general power grid (GCPV) (Fig. 14).

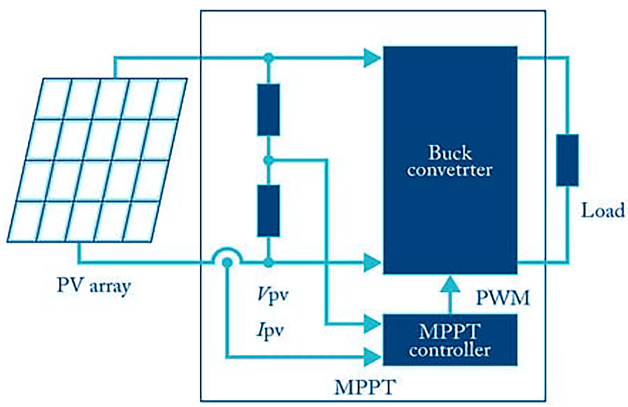

Figure 14. Autonomous SAPV system with MPPT inverter

Source: created by the authors

The volt-ampere characteristic (IV curve) is the most important parameter of a photovoltaic module, determining its electrical properties (Fig. 15). The maximum power point (MPP) on this curve corresponds to the optimal operating conditions of the module.

MPPT control using artificial neural networks (ANN) is being actively researched in photovoltaic systems (Roy *et al*., 2021). The neural network demonstrates the ability to adaptively track the maximum power point in a wide range of meteorological parameters. The system operation diagram is shown in Figure 16.

Fuzzy logic (FL) provides an effective tool for designing controllers in systems with high uncertainty. A hybrid technique combining FL with artificial neural networks, better known as Adaptive Neuro-Fuzzy Inference System (ANFIS) (Figure 17), serves as a tool for dealing with nonlinear systems (Nabavi-Pelesaraei *et al*., 2021).

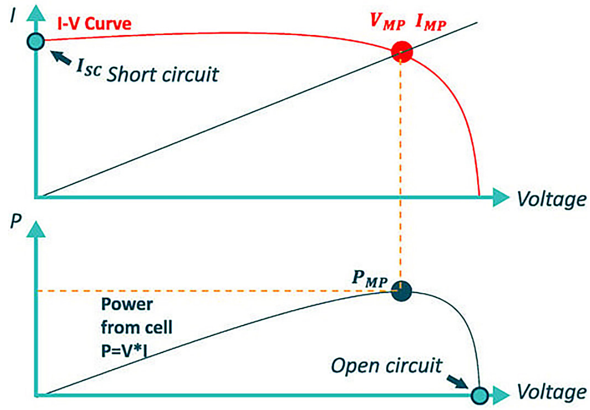

Figure 15. Volt-ampere characteristic of a photovoltaic module
Source: created by the authors

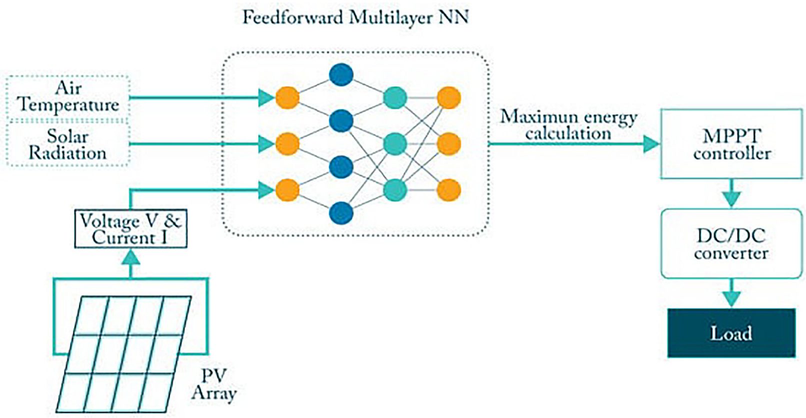

Figure 16. Neural network diagram for MPPT control
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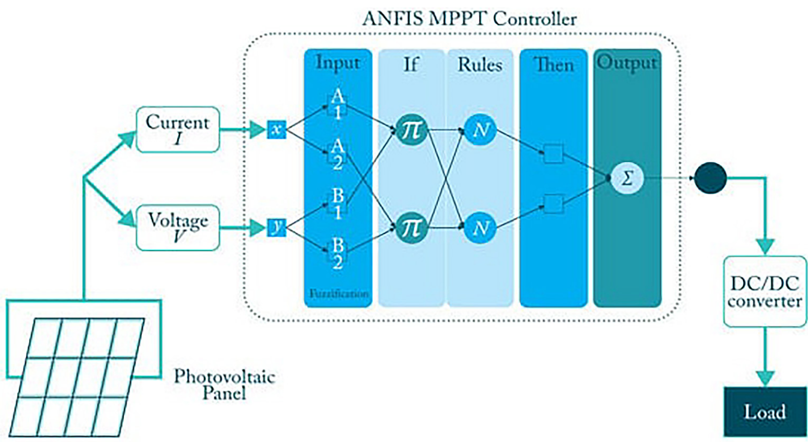

Figure 17. Block diagram of the ANFIS controller with 2 inputs
Source: created by the authors

Using a hybrid approach combining artificial neural networks and genetic algorithms in combination with the traditional P&O method allows optimizing the input data and increasing the efficiency of the MPPT algorithm. The scheme of such a solution is shown in Figure 18.

To improve the efficiency of solar energy conversion, it is proposed to use the MPPT algorithm based on artificial neural networks (Fig. 19). The model is trained on data obtained under various operating conditions, which allows it to adapt to dynamic changes in the external environment and ensure optimal operation of the system in a wide range of conditions (González-Castaño *et al.*, 2021). Figure 20 shows the DC/DC converter.

This figure illustrates the operating principle of a direct current to direct current (DC-DC) converter, where the listed elements play a key role in regulating electrical energy. The step-up converter, which operates on the principle of discontinuous conduction mode, consists of passive elements (choke, diode, capacitor) and an active element (switch). The P&O algorithm implemented in the converter control system ensures tracking of the maximum power point of the photovoltaic module by periodically changing the pulse width of the control signal (Osmani *et al.*, 2021). The disadvantage of the algorithm is the presence of output power fluctuations in the steady state, which can negatively affect the operation of subsequent elements of the system. Figure 21 illustrates the P&O algorithm.

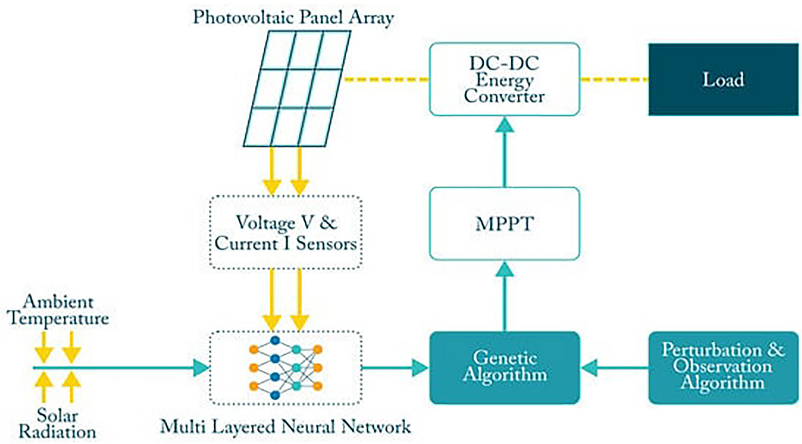

Figure 18. Structural diagram of a hybrid controller that optimizes solar battery energy production
Source: created by the authors

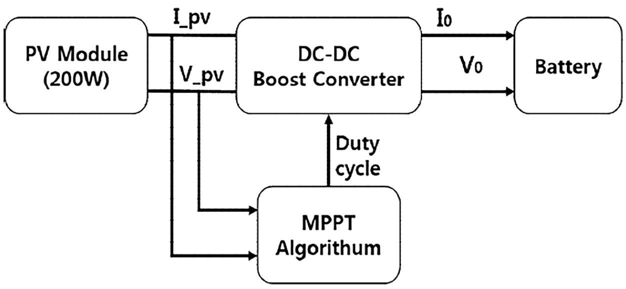

Figure 19. Solar energy production system
Source: created by the authors

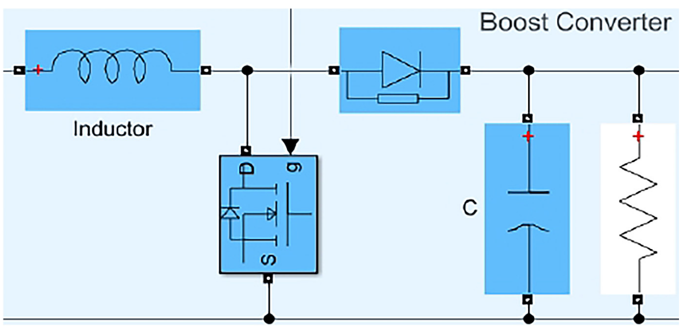

Figure 20. DC-DC converter
Note: D is a diode that ensures one-way flow of current in a DC-DC converter, s is a switch that controls the on/off of the circuit to regulate voltage and current, g is a control element for the key transistor used to change the state of the key, C is a capacitor that accumulates and smoothes the voltage, ensuring stable output voltage
Source: created by the authors

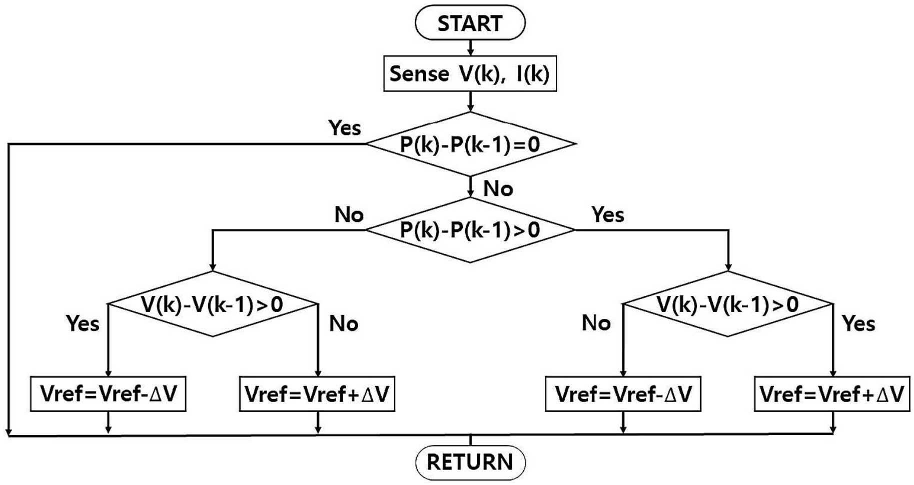

Figure 21. P&O Algorithm

Source: created by the authors

InC algorithm, based on the slope analysis of the voltage-power characteristic of a photovoltaic module, is one of the most common methods for tracking the maximum power point (Restrepo *et al.*, 2021). The method is characterized by high stability and ease of implementation and is widely used in combination with the P&O algorithm. Figure 22 illustrates the control principle of InC.

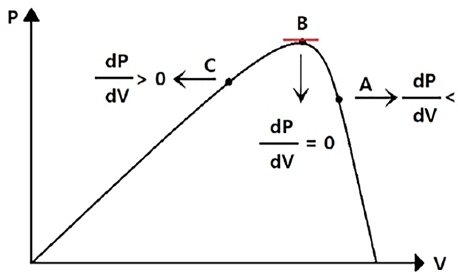

Figure 22. InC management theory

Source: created by the authors

Equation (17) has a positive slope of the VP characteristic curve, indicating the left MPP point, equation (18) has a negative slope, indicating the right MPP point, and equation (19) has a slope of 0, indicating the MPP point.

$$\frac{dp}{dV} = \frac{d(V \times I)}{dV} = I + V\frac{dI}{dV} > 0 \text{ (point C)}, \tag{17}$$

$$\frac{dp}{dV} = \frac{d(V \times I)}{dV} = I + V\frac{dI}{dV} < 0 \text{ (point C)}, \tag{18}$$

$$\frac{dp}{dV} = \frac{d(V \times I)}{dV} = I + V\frac{dI}{dV} = 0 \text{ (point C)}. \tag{19}$$

InC is an algorithm that overcomes the shortcomings of P&O and has the advantage that the solar panel output voltage always corresponds to the maximum power point voltage and does not deviate from the MPP tracking control. However, it requires significant computation and there is a high probability that the MPPT will not work due to sudden changes in solar radiation. Figure 23 illustrates the InC algorithm.

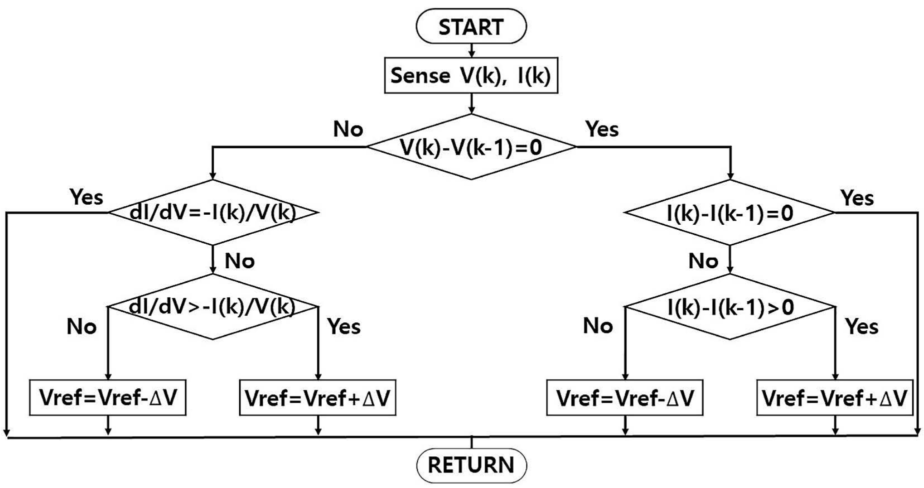

Figure 23. InC Algorithm

Source: created by the authors

Where V(k) and I(k) represent the current values of voltage and current, respectively, while V(k-1) and I(k-1) reflect their values at the previous step. dV and dI characterize the changes in photocurrent and photovoltage, and ΔV is the difference between the current and previous voltage values.

Neural networks in solar system management

The model combines the traditional MPPT algorithm with an artificial neural network to more accurately and quickly determine the maximum power point. The neural network, trained on current and voltage data under different lighting and temperature conditions, allows the MPPT algorithm to adapt to dynamic changes in the external environment (Fig. 24).

The model based on the neural network trained using the fuzzy logic controller enables the implementation of adaptive control of the DC-DC converter to track the maximum power point of the photovoltaic module. Taking into account the influence of temperature and solar radiation on the module parameters, the model provides higher efficiency compared to traditional MPPT algorithms. Figure 25 shows the photovoltaic modules and the neural network modules. Temperature and solar radiation are fed through IL Ctrl, which controls the photocurrent. The series resistance Rs and parallel resistance take into account the voltage drops and leakage current in the modules, and the output values are Ipv and Vpv. Figure 26 shows module schemes in fuzzy management.

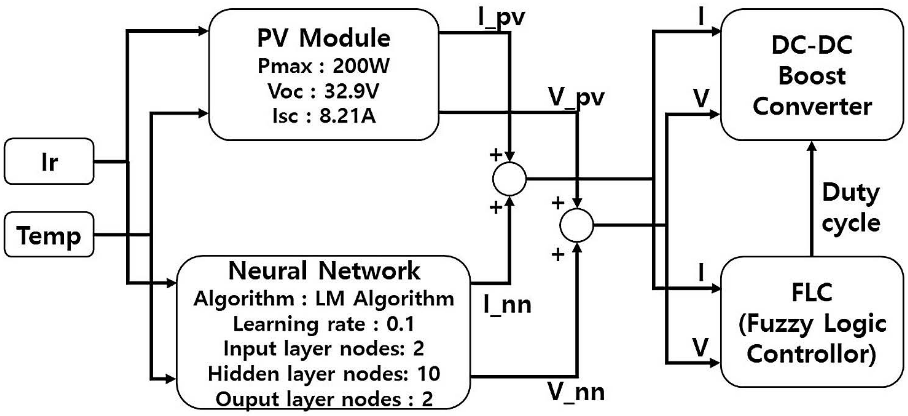

Figure 24. MPPT model

Source: created by the authors

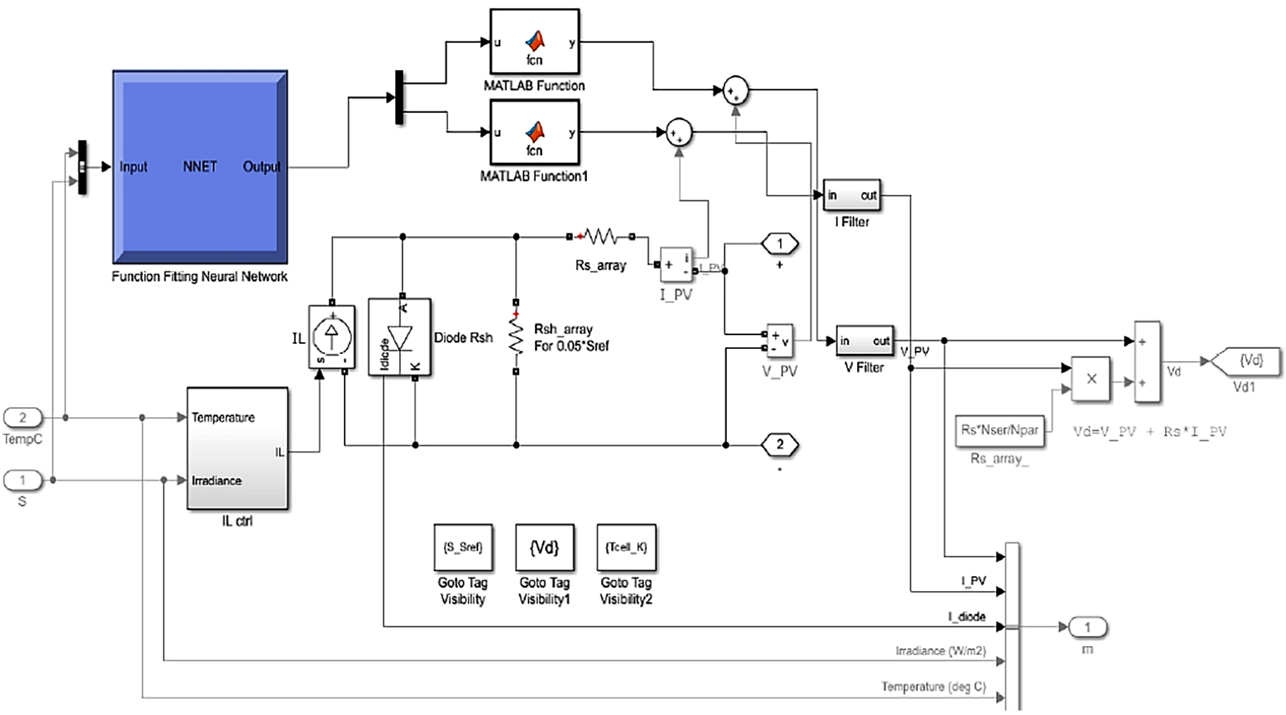

Figure 25. Photovoltaic and neural networks module

Source: created by the authors

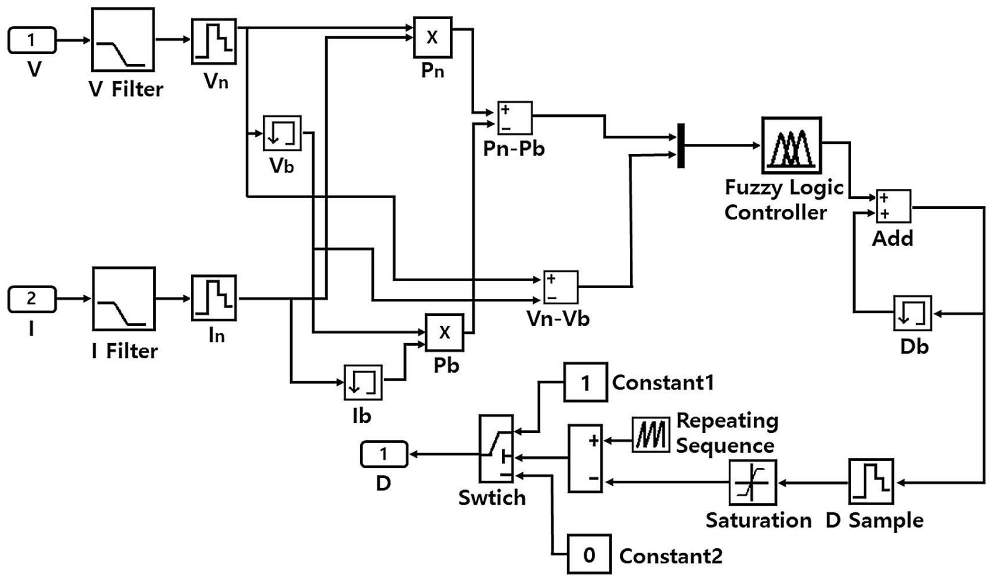

Figure 26. Fuzzy control circuit module

Source: created by the authors

Fuzzy Logic Controller (FLC) analyses how the solar panel power changes and sends a command to the converter to change the output voltage to achieve the best result. The input nodes of the artificial neural network are temperature and solar radiation, and the output nodes are the volt-ampere current MPP. The temperature range for the photovoltaic cells was from 0°C to 50°C in 5°C increments, and the solar radiation range varied from 200 to 1200 W/m² in 200 W/m² increments.

Since the temperature and solar radiation ranges to be used as input data are different, the data ranges must be the same or the distribution must be the same. In addition, since small input and output data are required for efficient AI training, the independent variables, temperature and solar radiation data, were normalized using min-max normalization, as shown in the equation (20):

$$\tilde{d_i} = \frac{d_i - \min(1{:}d)}{\max(1{:}d) - \min(1{:}d)}, \qquad (20)$$

where d_i – temperature and solar radiation data, min (1:*d*) represents the smallest value among each element, and max (1:*d*) represents the largest value among each element.

Nftool is a neural network tuning tool that performs training, validation, and testing by specifying the number of input units, output units, and mid-level nodes of an artificial neural network and choosing algorithms such as Levenberg Marquardt (LM), Bayesian regularization, and scaled confluent gradient. In this model, Nftool was used to build an artificial neural network with 2 input nodes, 10 mid-level nodes, 1 middle-level, and 2 output nodes. Figure 27 shows the structure of the artificial neural network.

Thus, the analysis of the theory and practice of modelling solar energy systems with ANN networks demonstrates the potential advantages of ANN in modelling these devices, such as high accuracy, generalization ability and short computation time compared to other theoretical and experimental modelling methods. Despite the simplifications applied in modelling based on ANN, their use eliminates the need to solve complex mathematical models.

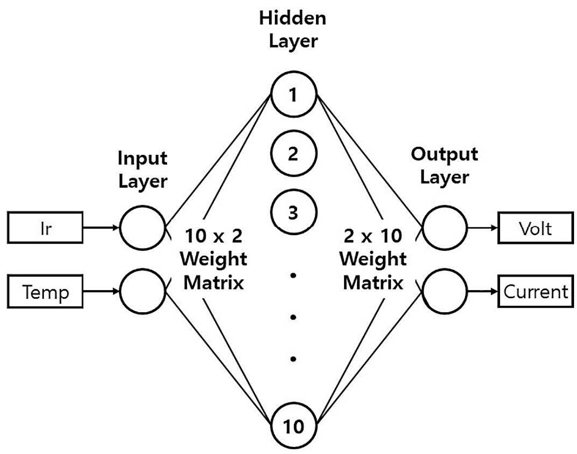

Figure 27. ANN structure

Source: created by the authors

DISCUSSION

In this study, a mathematical model of PV system based on artificial neural networks was developed and tested. The main result showed that the proposed model significantly improves the prediction accuracy of the maximum power point under varying environmental conditions such as illumination and temperature. The model also showed high real-time stability, which is important for improving the efficiency of solar power converters. This was also investigated by M. Talaat *et al*. (2022) where the results confirmed that predicting the maximum power point (MPP) of solar panels depends on the accuracy of tracking algorithms. These algorithms must take into account changing weather conditions to work correctly. The stability of the predictions is critical for optimizing power generation and reducing losses.

Studies by N. Ghadami *et al.* (2021) also showed that neural networks can learn efficiently from solar data and operating conditions. They are able to adapt to changing external factors, providing accurate control of the panels. This helps to improve system efficiency and reduce energy losses. It is worth noting that the use of neural networks in solar panel control not only improves their performance, but also minimizes the impact of human error. Automated systems with learning algorithms can respond faster to changes in operating conditions than traditional methods (Kudabayev *et al*., 2022). This is especially important in a variable climate, where the accuracy of prediction directly affects the performance of the entire system. The results confirmed that neural networks are more efficient than traditional maximum power tracking methods such as perturbation and observation and incremental conductance algorithms. Neural networks are better at adapting to changing conditions, which significantly reduces power loss under erratic solar activity (Stoliarov, 2024). This is especially important for systems operating in regions with variable climatic conditions, where traditional methods are less efficient. A. Zafar *et al.* (2022) concluded that traditional solar panel control methods are often based on fixed maximum power point tracking algorithms. Neural networks, in contrast, have the ability to learn and adapt to changes in external factors. This makes them more flexible and efficient in the long term.

In a study by F. Granata & F. Di Nunno (2021), it was found that climatic conditions such as cloud cover and temperature significantly affect the performance of solar panels. Algorithms based on neural networks show high efficiency in changing weather conditions by quickly adjusting the system settings. This allows maintaining an optimal level of power generation even under unfavourable climatic conditions. These results support the above study, as neural networks have shown high adaptability to different operating conditions. Unlike traditional methods, they respond faster to environmental changes, which helps to minimize energy losses (Smyk & Arkhypova, 2023). In addition, their self-learning ability enhances system performance in the long term. Another significant finding was that the developed model showed robustness to changes in input parameters such as solar radiation intensity and operating temperature. This indicates the high adaptability of the model to different operating conditions and its ability to work correctly with different types of solar panels. Thus, the proposed system can be applied in a variety of climatic zones and scales of solar installations.

Of note is the work of J. Jasiūnas *et al.* (2021), who also found that neural networks allow the system to adapt to rapid changes in environmental parameters such as light level and temperature. Due to its ability to learn from a large amount of data, the system can adjust its performance in real time. This increases the stability of power generation and reduces the risks of efficiency degradation. In turn, S. Gorjian *et al.* (2021) concluded that the developed neural network-based models can be successfully applied to both residential and industrial solar installations. Their versatility allows systems to be customized for different scales and operating conditions. This makes them attractive to a wide range of users, from private homeowners to large energy companies.

These findings are consistent with the thesis in the previous section, where the flexibility and adaptability of neural networks were discussed. Models using such networks are not only better able to cope with environmental changes, but are also more versatile in their application. This confirms their relevance for different types of solar installations and a wide range of climatic conditions. Experimental results have also demonstrated that automating the maximum power point tracking processes using neural networks reduces the operation and maintenance costs of PV installations. This is achieved by minimizing the need for manual calibration and continuous monitoring. Reducing human intervention in system operation not only reduces operating costs but also improves system reliability and durability (Shahini *et al*., 2024). M.S. Qureshi *et al.* (2024) also conducted a study, the results of which confirmed that the use of neural networks in solar panel control contributes to lower operating costs through more accurate prediction and optimized operation. The systems automatically adjust their operation, which reduces the need for regular maintenance. This reduces the cost of repairs and technical inspections, increasing cost efficiency. J.F. Derakhshandeh *et al.* (2021) also found that automating solar panel control processes using neural networks reduces the need for constant human monitoring. Algorithms are able to independently monitor and adjust system operating parameters in real time. This not only reduces the risks of human error, but also makes operation more convenient and efficient (Szafraniec *et al*., 2021).

Comparing the data obtained in the course of research, there is a clear trend towards cost reduction and increased efficiency due to the automation of processes. Neural networks can minimize human involvement and optimize the operation of solar systems in the face of various external factors (Rexhaj, 2024). This emphasizes the importance of adopting such technologies to improve overall performance and reduce operating costs. In addition, the proposed mathematical model opens up opportunities for further research in the field of optimizing the performance of solar converters. This includes the development of methods for integrating weather forecasting and solar panel angle control to further improve the efficiency of power systems. Combining such approaches with neural network algorithms can significantly improve the management of energy resources.

G. Li *et al.* (2022) concluded that the field of solar energy continues to evolve, opening up opportunities for further research in optimizing panel performance and energy storage. One area of focus is improving neural network-based algorithms to improve their accuracy and responsiveness. Research into integrating solar systems with other renewable energy sources to create hybrid solutions is also relevant. S.U. Khan *et al.* (2023) revealed that integrating artificial (AI) intelligence with weather forecasting systems can improve real-time control of solar panels. AI can analyse weather data and adjust panel operating parameters to maximize energy generation. This enables more accurate and efficient utilization of solar energy, especially in regions with variable climatic conditions.

When analysing the results of the study, it is clear that integrating AI with weather forecasting significantly improves solar panel management. Such technologies not only improve the accuracy of the systems, but also allow them to adapt to rapidly changing climatic conditions. This opens new perspectives for a more efficient utilization of renewable energy sources and their integration into the energy networks of the future. In conclusion, the developed model shows significant potential for solar energy applications. The increased accuracy of maximum power prediction, reduced operating costs and improved system stability make this approach promising for widespread deployment in the renewable energy sector, especially under intermittent solar conditions.

CONCLUSIONS

As a result of the conducted study of mathematical modelling of solar electric power converters, several key conclusions have been reached, reflecting the efficiency and relevance of these technologies. The developed mathematical model based on the equivalent circuit of photovoltaic cells has demonstrated high accuracy in describing the basic electrical characteristics of solar modules. The model takes into account the influence of factors such as ambient temperature, light intensity and resistance, which allows a detailed analysis of the power output of the converters under different conditions.

The equations used to describe the photocurrent and saturation inverse current were the basis for creating an efficient simulation in the MATLAB/SIMULINK environment. This simulation provides the opportunity to investigate the behaviour of solar converters under different environmental conditions, which in turn improves the prediction of their performance and life cycle. The implementation of maximum power point tracking algorithms has had a significant impact on the performance of solar systems. The results of the study showed that the algorithms based on artificial neural networks provide more accurate and faster maximum power point detection compared to traditional methods such as lift-and-watch and incremental conductance. This significantly improves the overall performance of solar converters.

The results of the study highlight the importance of mathematical modelling and the application of advanced algorithms to optimize the performance of solar power converters. These findings offer new opportunities to improve their efficiency and incorporate them into sustainable energy supply systems, thereby promoting renewable energy development and reducing dependence on conventional energy resources. The limitations of this study are the focus on mathematical modelling of solar electric power converters without considering the actual operating conditions and environmental influences, which may affect the accuracy of the results obtained. It is necessary to study the impact of different materials and solar cell manufacturing technologies on their efficiency and durability, as well as to assess the economic feasibility of introducing innovative solutions into the mass production of solar electric power converters.

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CONFLICT OF INTEREST

None.

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Математичне моделювання сонячних перетворювачів електроенергії

Анотація. Дослідження було проведене для розробки математичної моделі фотоелектричних систем з використанням штучних нейронних мереж. Було створено математичну модель фотогальванічної системи, реалізовано процес симуляції з урахуванням ключових параметрів, а також застосовано метод відстеження максимальної точки потужності для підвищення ефективності роботи системи. Під час дослідження було розроблено та протестовано математичну модель фотоелектричної системи на основі штучних нейронних мереж, призначену для підвищення ефективності роботи сонячних панелей. Модель показала високу точність у прогнозуванні точки максимальної потужності за мінливих умов навколишнього середовища, таких як освітленість і температура. Аналіз отриманих даних продемонстрував, що використання нейронних мереж для відстеження максимальної потужності значно зменшує втрати енергії порівняно з традиційними методами відстеження. Експериментальні результати підтвердили, що запропонований підхід забезпечує більш стабільне і точне визначення точки максимальної потужності в реальному часі. Висновки показали, що впровадження такої системи може значно підвищити загальну продуктивність фотоелектричних установок, особливо в умовах непостійної сонячної активності, що робить її перспективною для застосування в різних кліматичних зонах. Крім того, модель показала стійкість до зміни параметрів вхідних даних, що робить її адаптивною до різних типів сонячних панелей і умов експлуатації. Також було виявлено, що система на основі нейронних мереж знижує витрати на експлуатацію та обслуговування фотоелектричних установок за рахунок мінімізації необхідності ручного калібрування і моніторингу. Отримана в результаті модель дасть змогу підвищити точність і ефективність відстеження максимальної потужності сонячних панелей за мінливих умов навколишнього середовища

Ключові слова: максимальна потужність; освітлення; температура; прогнозування; нейронні мережі

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Analysis of radio relay station control system using IT-technologies

Abstract. The study addressed the theoretical analysis of radio relay station control systems using modern information technologies. The study aimed to identify the potential for improving the performance, reliability and cost-effectiveness of such systems. The analysis investigated advanced sensor technologies, automation algorithms and monitoring techniques that could significantly reduce maintenance costs and speed up fault response. Key aspects affecting the performance of radio relay stations were considered, including the impact of climatic conditions and various operational scenarios. The importance of automation integration to improve system reliability and reduce the impact of human error was emphasised. Compliance of the proposed solutions with international radio relay standards, which simplified integration with existing networks and the possibility of future modernisation, was also highlighted. The results of the study substantiated the necessity of automation of radio relay systems and created a theoretical basis for their further development and improvement, which opened new opportunities for improving operational characteristics and increasing resistance to potential failures. The implementation of new approaches to data management and analysis was addressed, ensuring quick response to changes during operation as well as resource optimisation. These aspects provided a competitive advantage in a rapidly changing telecommunications technology environment, emphasising

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the importance of flexibility and adaptability of systems for efficient operation. As such, the study of the theoretical foundations of automation can be used as a basis for practical recommendations for the implementation of innovative technologies in radio relay station management

Keywords: communication automation; sensor modules; machine learning; remote monitoring; reliability enhancement; economic efficiency

INTRODUCTION

The development of automated control technologies has become an integral part of many industries, including telecommunications systems. Radio relay stations are substantial in the transmission of data over long distances, especially in remote and inaccessible regions where other means of communication are limited. The efficiency of such stations, their reliability and cost-effectiveness directly depend on the quality of control and monitoring. However, traditional control systems for radio relay stations have many disadvantages associated with manual operation, insufficient response time to faults, and significant maintenance costs. These factors necessitate the search for new solutions to optimise the operation of radio relay stations.

One of the key areas for improving the management of such stations is the application of modern IT technologies and data processing algorithms, including machine learning and sensor-based analyses. With the help of such technologies, the performance and reliability of radio relay stations can be significantly improved by predicting failures and automating routine operations. Scientific research in recent years confirms the significance and promising potential of such approaches for telecommunication facilities management. Researchers such as R.M. Thomas & S. Malarvizhi (2022), point out the need to improve the responsiveness of management and suggest the use of machine learning algorithms to monitor the state of equipment. I. Rojek *et al*. (2023) addressed the potential to improve failure prediction in telecoms networks using sensor data, and the impact of such systems in reducing equipment downtime. These works show the potential of data analytics technologies to reduce operational costs and improve station reliability. Moreover, I. Rojek *et al*. (2022) analysed the economic aspects of implementing automated control systems, and how automation can reduce maintenance costs and improve the overall economic efficiency of radio relay stations.

However, most existing research focuses on data analysis and processing algorithms, leaving less explored the integration of these technologies within an integrated radio relay station management system that accounts for operation in different climatic conditions and system scalability. At the same time, modern realities require the creation of solutions that can work effectively in remote areas with minimal operator involvement. S. Sadiki *et al.* (2018), who analysed the implementation of sensor systems for monitoring telecommunications equipment, showed that automated systems significantly reduce the need for service personnel and reduce the likelihood of human error. Nevertheless, specific aspects of the operation of such systems in radio relay communications, especially in the context of frequent climate change, require further study and adaptation.

At the same time, the introduction of secure transmission channels and modern communication modules remains an important part of the modernisation of radio relay stations, as this reduces the risk of leakage and ensures a high level of security of information transmission (Smailov *et al*., 2023). T. Mazhar *et al*. (2023) addressed transmission security in telecommunication systems and emphasised the importance of secure communication modules to prevent cyberattacks and improve network stability. But despite this, there is a gap in the scientific literature related to the development of integrated control systems that could integrate sensor data, prediction algorithms and communication modules into a single infrastructure. This suggests that an established integrated control system for radio relay stations can not only improve the reliability of operation but also significantly reduce station operation and maintenance costs. The scientific literature devoted to the automation of radio relay stations and the application of modern IT technologies in telecommunication systems is extensive and diverse. The main areas of research include control automation, sensor technologies, machine learning algorithms, economic efficiency of automation, integration of secure communication modules and adaptation of systems to climatic conditions.

M. Wilson *et al.* (2020) discussed automated control algorithms that aim to improve the efficiency of radio relay stations. The study emphasises the need for rapid response to failures and the development of systems that can automatically adapt to changing conditions. Several papers, including the research of J.L. Álvarez *et al*. (2021), emphasised the use of sensor technologies for equipment condition monitoring. These works demonstrate how the integration of sensors into radio relay station control helps to reduce downtime and improve reliability. A.P. Kane *et al*. (2022) investigated the use of machine learning to predict potential equipment failures. These algorithms can process large amounts of data and extract useful information for management decisions.

An important area of research is related to the security of data transmission. J. Pochmara & A. Świetlicka (2024) addressed the implementation of secure communication channels, which reduces the risk of leaks and increases the resistance of telecommunication networks to cyberattacks. Some studies, such as one by S. Sadiki *et al*. (2018), investigated how climatic changes affect the operation of radio relay stations and the need to adapt control systems in different climatic zones. Thus, the present study aimed to develop a system that will improve the performance of radio relay stations, minimise the need for manual intervention and ensure reliable operation in different climatic zones. The main hypothesis of the study was that the use of an automated control system that integrates data acquisition modules, analysis algorithms and secure communications would reduce operating costs, improve station reliability and ensure system resilience to climatic changes.

LITERATURE REVIEW

Automation of radio relay control involves many aspects, including control mechanisms, monitoring systems and modern IT technologies. Automation has become an important aspect in many fields, particularly in telecommunications. According to a study by M. Wilson *et al*. (2020), new automated control algorithms significantly improved the management efficiency of telecommunication systems. The authors emphasise the importance of adaptive solutions that reduce the response time to problems. J.L. Álvarez *et al*. (2021) addressed the integration of sensor technologies in communication systems. They emphasise that real monitoring helps to reduce maintenance costs and improve reliability. This is also supported by A.P. Kane *et al*. (2022) who pointed out the role of machine learning in predicting maintenance of telecommunication equipment.

Security is an important aspect of automation. J. Pochmara & A. Świetlicka (2024) addressed the importance of secure data transmission channels to prevent cyberattacks. Security issues of automated telecommunication systems were also covered by S. Ainslie *et al*. (2023), who described modern methods of real-time monitoring and their impact on management decisions. A.O. Osahenvemwen & B.E. Omatahunde (2018) investigated the impact of climate conditions on telecommunication networks, pointing out the need to develop adaptive solutions to improve reliability in the face of climate change. This important observation was also supported by I. Rojek *et al*. (2023), who proposed automated systems to reduce the likelihood of outages in remote areas. In fact, despite the plethora of studies, many of them focus on individual aspects, leaving insufficient attention to the integration of technologies within complex systems. This is confirmed by a review of the works of K. Jakobsen *et al*. (2023), who analysed the challenges of automation in rural areas, emphasising the need for technical improvement.

Some studies also emphasise the economic benefits of automation. For instance, S. Berhe *et al*. (2023) presented predictive maintenance strategies that reduce the cost of operating equipment. This correlates with the economic benefit analyses conducted by U.R. Kamboh *et al*. (2017) who highlighted the main business benefits of automation. The impact of the Internet of Things (IoT) on telecommunication systems is also an important aspect. I. Appiah *et al*. (2023) pointed out that the integration of IoT into telecommunication networks can significantly improve automation and management processes, providing increasing efficiencies. This emphasises the need to develop and implement new protocols and standards that can ensure the smooth operation of these technologies in different environments.

According to a study by A. Aljohani (2023), predictive analytics is becoming more and more relevant for network management as it enables timely responses to potential problems. They emphasise the importance of data for making informed management decisions. Efficient processing of big data also opens new opportunities to optimise network processes and improve customer service. Equally significant are the studies by N. Zhao *et al*. (2023), which analyse the integration of communication technologies. They emphasise the importance of combining different technologies to improve the efficiency of systems. In addition, the works of L. Nazareno & D.S. Schiff (2021) investigated the impact of human factors on automated systems, emphasising the need to train and adapt personnel to new technologies. Lastly, the research of K. Park *et al*. (2023) analysed the scalability issues of automated control systems, pointing out the need to adapt technologies for different sizes of telecommunication networks.

In addition to the studies, S.G. Gavrila *et al*. (2023) significantly contributed to the overall research, as they addressed the ethical aspects of automation in telecommunications, emphasising the need to account for the social consequences of the introduction of new technologies. They emphasise that automation should address the interests of consumers and society. Another noteworthy contribution is the study by Y. Lee *et al*. (2023), which addressed the issues of sustainable development of telecommunication systems in the context of automation. The authors highlighted the need to integrate environmental aspects into automation strategies. The study by P.D.B. Kenfack *et al*. (2023) is also noteworthy, as it analysed the latest technologies that can be used to automate radio relay stations, emphasising the importance of innovation in this area. Lastly, the study by A.K. Aliyu *et al*. (2015) addressed the energy efficiency of automated systems, which is critical to reducing costs and increasing sustainability in the face of climate change. Thus, the literature review revealed a wide range of studies on automation in telecommunications, covering various aspects, from economic benefits to security and the impact of climatic conditions. However, despite significant progress, there is a need to further explore the integration of technology into integrated management systems, which will form the basis for future research in this area.

Additionally, it is possible to note that the growing interest in automation in telecommunications is linked to global trends in digitalisation and sustainable development. This underscores the importance of continuously exploring new technologies and methods that could have a significant impact on the future of the industry. Successful automation can significantly improve productivity and cost-effectiveness, which in turn will affect the competitiveness of companies and the quality of services provided.

MATERIALS AND METHODS

The study aimed to assess the effectiveness of automation of radio relay stations by analysing data collected in previous experimental studies, as well as by summarising the practical experience of implementing automated systems in telecommunications. In this context, a comprehensive analysis of existing publications and practical experience regarding the impact of automation on key indicators such as fault response time, maintenance costs, reliability and cybersecurity of telecommunications systems was conducted (Table 1).

Table 1. Sources for analysing the main areas of telecommunications systems automation

Source	Primary research topic
M. Wilson *et al.* (2020)	Evaluation of the efficiency of automation algorithms at radio relay stations.
J. Pochmara & A. Świetlicka (2024)	Modern technologies in the field of telecommunications system security.
S. Sadiki *et al.* (2018)	The impact of the Internet of Things on the performance of radio relay stations.

Source: compiled by the authors

To systematise information on modern technological solutions in automation, several key aspects were considered that reveal the complexity and versatility of processes. Firstly, the system fault response rate determined how quickly and efficiently the system could detect and correct the problem. In automated telecommunications systems, this was particularly important to minimise equipment downtime, which reduced financial losses and improved service availability. Automatic monitoring systems analysed anomalies in real time and quickly notify operators, reducing delays in response. Maintenance costs were also a major concern. The introduction of automated technology could significantly reduce operating costs as systems can perform diagnostics, identify potential faults and schedule maintenance. This reduced the number of unscheduled repairs and reduced the likelihood of costly failures.

Another important aspect was the level of system reliability, which determined how resilient the system was to malfunctions and failures. The implementation of intelligent monitoring algorithms and predictive analyses could prevent faults before they occured, thus increasing the overall level of reliability. The integration of new technologies such as the Internet of Things (IoT) and predictive algorithms was addressed. IoT maked it possible to monitor equipment status remotely by collecting data from various sensors in real-time, which opened new possibilities for analysing and managing the network. Predictive algorithms, in turn, could predict potential problems based on accumulated data, thus creating a more resilient and manageable system. Interviews with telecoms specialists were also used to substantiate the relevance of automation (Xin *et al.*, 2023). The data collected covered various parameters such as fault response times, maintenance costs and security metrics including the frequency of cyber threats and their impact on data.

The analysis of the impact of automation on the integration of new technologies also covered methods of equipment condition monitoring and the use of machine learning algorithms. Machine learning was analysed in terms of predicting potential failures and replacing equipment on time to reduce downtime and improve overall network stability. Security materials were examined to assess the systems' ability to protect data from cyber threats. Statistical methods for processing the collected data were used to identify correlations between automation and improved radio relay station performance. Thus, the systematic approach was used to conduct a generalised analysis of the effectiveness of automated systems and outline areas for further optimisation of radio relay stations by reducing the influence of the human factor on their operation in different climatic conditions and regions.

RESULTS

Modern sensors used in the automation of radio relay stations provide high accuracy in monitoring the condition of equipment. They not only quickly detect faults, but also predict component wear, which is significant in improving system reliability. The use of real-time sensors allows for a quick response to changes in the condition of equipment, which reduces the likelihood of emergencies and increases the overall stability of the system.

By integrating sensor technology into the monitoring process, it is possible to significantly improve resource management and reduce downtime. For instance, predictive analytics based on sensor data can identify potential problems before they occur, reducing maintenance costs and improving safety. Adoption of such technologies also helps optimise maintenance schedules by enabling more accurate scheduling of inspections and component replacements based on real equipment health data. Sensors not only increase responsiveness to faults but also enable proactive management, which is an important aspect of improving the efficiency of telecom systems (Babak *et al.*, 2021). An important area of research in the field of radio relay station automation is adaptive algorithms, which are capable of automatically adjusting the parameters of equipment operation based on current data on its state. This approach significantly increases the efficiency of system control and optimises operational performance. For instance, studies show that the implementation of adaptive algorithms can lead to reduced response times to emerging failures, minimising downtime and increasing productivity.

Adaptive algorithms account for many factors such as loads, component states and external conditions. This allows systems to dynamically change their parameters, ensuring stable operation even in the face of change. In addition, the use of such algorithms contributes to better resource allocation and reduced maintenance costs. As a result, adaptive algorithms are becoming a key element for improving the reliability and resilience of radio relay stations by enabling proactive responses to potential faults. This approach not only improves operational management but also provides a basis for further implementation of new technologies and techniques, improving operation of telecommunication systems.

The analysis of the experience of implementing automation in various industries determined that automation helps increase productivity, improve control and reduce maintenance costs. Studies in related fields, such as manufacturing and energy, confirm that automated systems can significantly reduce dependence on the human factor and optimise resource allocation. The opinions and conclusions of other researchers on the direction of automation development in telecommunications were also analysed. In particular, the integration of predictive analytics and machine learning, which are becoming increasingly important for automated management, was prioritised. Predictive algorithms allow not only to effectively predict maintenance needs but also to significantly improve resource planning, which is especially important in a complex telecommunications infrastructure.

Research shows that incorporating machine learning into a control system helps to analyse vast amounts of data, identifying patterns and anomalies that can indicate potential faults. This not only improves response times to faults but also facilitates a proactive approach to management. Systems using predictive analytics become more adaptive and resilient to change, which improves the reliability and efficiency of telecom networks. Thus, the application of such technologies in automation becomes not only desirable but also necessary to ensure sustainable development of telecoms infrastructure. Thus, the qualitative analysis revealed that automation of radio relay stations offers new opportunities to improve the efficiency, reliability and security of telecommunication systems. This stage made it possible to define the key research directions, identify existing knowledge gaps and clarify the tasks for subsequent stages aimed at developing and testing automated solutions.

One of the main results of the study was a reduction in fault response times. Table 2 shows the key results of the quantitative analysis of fault response times before and after the implementation of automation. Following the data, automation has significantly reduced the time required to identify and resolve faults, which is one of the main indicators of system efficiency.

Table 2. Key results of the quantitative time analysis

Parameter	Before automation (min)	After automation (min)	Decrease (min)
Average reaction time	45	15	30

Source: compiled by the authors based on I. Rojek *et al*. (2023), Y. Xin *et al*. (2023)

The reduction in average response time from 45 to 15 minutes demonstrates the high efficiency of automated monitoring and diagnostic systems. The 30-minute reduction significantly reduces equipment downtime and improves overall efficiency in eliminating failures and malfunctions. This data confirms that the introduction of automation in the management of radio relay stations improves the response to critical events, optimising the maintenance process and increasing the reliability and performance of the telecommunications system. A 66.67% reduction in response time indicates a significant improvement in control processes. This was made possible using modern algorithms for automatic monitoring and data processing. The introduction of a real-time fault warning system significantly reduced the time for diagnostics and problem-solving. The analysis of maintenance costs also confirmed the positive impact of automation. Table 3 summarises the annual costs before and after automation.

Table 3. Annual costs before and after automation

Parameter	Before automation (USD)	After automation (USD)	Decrease (USD)
Annual costs	6000	4000	3000

Source: compiled by the authors based on M. Wilson *et al.* (2020)

A 40% reduction in costs confirms the effectiveness of automation. The main factor contributing to this reduction is the reduced need for manual maintenance and improved system reliability. Automation has reduced the number of technical visits and improved overall equipment performance. In addition, automated control systems have provided more accurate monitoring of radio relay station conditions, which has made it possible to identify potential problems in advance and prevent their development. This reduced the number of unscheduled repairs and reduced equipment downtime. As a result, companies that implemented automation not only reduced operating costs but also improved the quality of their services. Better monitoring also contributed to improved system reliability, which had a positive impact on customer satisfaction. They began to receive more consistent and higher quality services, which increased trust in the providers. Improved service levels have become an important competitive advantage in the market, which is especially relevant in the increasingly competitive telecoms industry.

Automation has not only optimised internal processes but also created a more positive brand perception among customers. Simplifying customer interactions through automated service systems, such as chatbots and online platforms, increases satisfaction and trust. This, in turn, opens up new opportunities for business growth and expansion, allowing the company to attract more customers and improve its reputation in the market. Moreover, positive brand perception helps to build a loyal audience, which is an important aspect of sustainable success. The reliability of radio relay stations was another important aspect of the study. Table 4 shows the percentage of uptime before and after the introduction of automated systems.

Table 4. Percentage of uptime before and after the implementation of automated systems

Parameter	Before automation (%)	After automation (%)	Increase (%)
Reliability	85	98	13

Source: compiled by the authors based on A.P. Kane *et al*. (2022)

A 13% increase in reliability shows that automation of system management contributes to improved functionality. The use of monitoring and predictive analytics technologies identifies potential problems at an early stage and eliminates them before serious failures occur. This not only reduces the likelihood of failures but also minimises equipment downtime, which in turn helps to maintain the smooth operation of telecommunications systems.

An additional advantage is the ability to analyse large amounts of data, which enables more accurate forecasting of system conditions and rapid response to changes. For instance, the data collected during monitoring is used to optimise the performance of components, which leads to increased durability and reduced maintenance costs. Data security in telecommunications systems was also the subject of research. Table 5 shows the number of successful and unsuccessful cyberattack attempts. The 66.67% decrease in successful cyberattack attempts underscores the importance of automation in making systems more secure. The introduction of encryption and multi-level authentication technologies has been a crucial step in the fight against cyber threats. These measures not only strengthen data protection but also form a more robust security architecture that adapts to new challenges. Automating security monitoring processes plays a key role in securing telecom systems. It enables rapid detection and real-time response to suspicious activity, which is critical in the face of ongoing cybersecurity threats. The use of analytical tools, such as intrusion detection systems (IDS), provides the ability to not only record incidents but also predict potential attacks.

Table 5. Number of successful and unsuccessful cyberattack attempts

Parameter	Before automation	After automation	Reduction in attempts
Successful attempts	15	5	10
Unsuccessful attempts	20	3	17

Source: compiled by the authors based on J. Pochmara & A. Świetlicka (2024)

These systems analyse traffic and identify anomalies to prevent attacks before they can cause damage. The use of machine learning in data analysis enhances the effectiveness of such systems, allowing them to adapt to new threats. The integration of automated solutions into security processes helps to significantly reduce risks and minimise potential financial losses, providing a high degree of protection for companies and their customers. Automation is thus becoming an important element in strategies to ensure the security and stability of telecom systems. In addition, automation of access and user rights management minimises the human factor that often causes vulnerabilities. Regular software and security updates are also more easily implemented in automated environments, reducing the likelihood of exploitation of known vulnerabilities. Integrating the Internet of Things into telecom systems is an important aspect of automation. IoT systems allow for better monitoring and control of stations. Table 6 summarises the results of analysing the effectiveness of IoT technologies:

Table 6. Results of analysing the effectiveness of IoT technologies

Parameter	Before IoT implementation	After IoT implementation	Increase in efficiency (%)
Management efficiency	70	90	20

Source: compiled by the authors based on S. Sadiki *et al*. (2018) and I. Appiah *et al*. (2023)

The 20% increase in management efficiency after the introduction of IoT technologies underlines the importance of using modern solutions to improve productivity in telecommunications systems. Automated systems based on IoT provide continuous real-time data collection and analysis, which significantly improves management and monitoring processes.One of the key benefits of the IoT is the ability to integrate various devices and sensors that provide a stream of up-to-date information about the state of equipment and the environment. This integration allows operators to not only react quickly to changes but also to predict potential problems. For example, sensors can detect deviations from normal equipment operation, enabling serious malfunctions to be prevented in advance (Nussibaliyeva *et al.*, 2024). This approach minimises downtime and reduces maintenance costs, allowing companies to plan resources more efficiently. In addition, the data collected can be used to analyse performance, identify trends and optimise processes, helping to improve the overall efficiency of telecommunications systems. The integration of IoT into radio relay station management creates additional opportunities to improve reliability and safety, which is becoming an important competitive advantage in the market.

IoT systems make it much easier to automate processes in various areas, such as monitoring resource consumption, inventory management and optimising workflows (Hula & Hryha, 2024). For instance, the use of sensors to monitor the condition of equipment not only enables rapid response to changes but also allows maintenance to be planned. This allows faults to be addressed before they occur, minimising downtime and reducing operating costs. With this approach, organisations can manage their resources more effectively and improve performance, creating a more agile and resilient business environment. Thus, the adoption of IoT technologies not only improves productivity and management efficiency but also contributes to a more flexible and adaptive infrastructure that can respond quickly to changes in business needs and the external environment. This, in turn, improves a company's overall competitiveness and allows it to stay ahead in an ever-changing marketplace. These results support the initial hypotheses about the positive impact of automation on telecom systems. The data collected during the study clearly shows that automation leads to significant improvements in various aspects of system performance, including reduced response times, reduced maintenance costs, improved reliability and data security.

Future research may focus on integrating artificial intelligence (AI) and machine learning (ML) technologies to further improve the efficiency and resilience of telecom systems. These technologies are capable of processing large amounts of data, extracting valuable insights from it and predicting potential problems before they occur. For instance, AI can be used to optimise network processes and ML can be used to adapt systems to changing conditions and loads (Lien *et al.*, 2019). Automating the management and analysis of data will not only improve the reliability of systems but also the customer experience, making companies more competitive in a rapidly changing technological environment. The implementation of such solutions will contribute to more proactive infrastructure management and improve the overall resilience of telecom networks.

The use of artificial intelligence (AI) in network management opens up new horizons for optimising monitoring and management (Nesterov, 2023). AI allows systems not only to respond quickly to changes in operations but also to predict potential problems, eliminating them before they occur. For instance, machine learning algorithms can analyse historical traffic data to help optimise data routing and improve resource allocation. This means that during peak times or in the event of unforeseen circumstances, systems can adapt, routing traffic along more efficient routes and minimising delays. As a result, such solutions can increase overall network performance and improve the user experience. AI can also be integrated into automated control systems, which further speeds up the decision-making process and minimises the human factor.

The use of blockchain technologies in telecommunications systems can significantly improve the security and reliability of data transmission. Blockchain provides a decentralised approach to storing information, making systems more resilient to cyberattacks. Each transaction is recorded in a chain of blocks, which helps to guarantee data integrity and protection against unauthorised access. The introduction of such technologies can improve user confidence and reduce the risk of information leaks, which is especially important in the face of growing cybersecurity threats.

DISCUSSION

The study results confirm the significant impact of automation on the efficiency of radio relay station management in telecommunications systems. Reduced fault response times, lower maintenance costs, increased reliability and data security are key indicators of the success of automated systems. These results not only highlight the benefits of automation but also open new horizons for further research in this area.

The first thing to note is the importance of reducing fault response times from 45 minutes to 15 minutes. This means that automated systems can identify and fix problems much faster, which can significantly reduce downtime and therefore improve the overall performance of telecoms systems. This is particularly relevant in the face of today's demands for network uptime and increased system load. Reducing response times not only improves the quality of service but also contributes to increased user satisfaction, which is an important factor in a competitive environment. Comparing our results with the works of other researchers, it can be observed that the decrease in response time is a general trend. For instance, the study by M. Wilson *et al*. (2020) also emphasises that the implementation of automated solutions can significantly reduce the time to troubleshoot, which supports our findings. However, not all studies focus on such significant improvements. Some authors, such as D. Xu *et al*. (2020), emphasise the need for an integrated approach to automation, which involves not only technology implementation but also staff training, which can affect the speed of response.

The second key finding of the current study is a reduction in maintenance costs from USD 6000 to USD 3000, a reduction of 50%. This reduction supports the hypothesis that automation not only improves efficiency but also reduces costs. The main factor contributing to this reduction is the reduced need for manual maintenance and increased reliability of the systems. J.L. Álvarez *et al*. (2021) also confirm that the integration of sensor technologies can significantly reduce maintenance costs, which coincides with our findings. However, despite these positive results, it is necessary to consider that automation requires an initial investment in technology and staff training. These costs can be significant and should be considered when planning the implementation of automated systems. Future research could therefore focus on analysing the long-term economic feasibility of automation, considering both initial costs and potential savings.

A 13% increase in system reliability is also a significant result. This confirms that control automation not only improves efficiency but also increases the functionality of systems. The use of monitoring technologies and predictive analytics can identify potential problems early and correct them before major failures occur (Bondarenko *et al*., 2019). A.P. Kane *et al*. (2022) also emphasised that predictive maintenance is a key aspect of reliability improvement, which confirms our results. However, following M. Polakova-Kersten *et al*. (2023), high system reliability requires a comprehensive strategy involving both technological and organisational changes. Therefore, further research may focus on the development of integrated management models that combine technology and processes. The 66.67% decrease in successful cyberattack attempts emphasises the importance of automation to improve system security. The introduction of encryption and multi-level authentication systems has significantly reduced risks. This is also consistent with the works of J. Pochmara & A. Świetlicka (2024) who emphasise the importance of secure data channels. Nevertheless, security remains a complex and multifaceted problem. As emphasised by A.O. Osahenvemwen & B.E. Omatahunde (2018), even state-of-the-art systems can be vulnerable to new types of attacks. Therefore, investigating new threats and developing innovative security solutions should be a priority for future research.

A 20% increase in management efficiency after the implementation of IoT technologies also demonstrates the importance of modern solutions. Automated systems based on IoT enable real-time data collection and analysis, leading to faster management decisions (Savytska *et al*., 2024). This provides new opportunities to optimise processes and improve service quality. A comparison of our results with studies by other authors shows that the adoption of IoT technologies is a recognised practice. N.A. Nanjar *et al*. (2024) emphasise that the integration of IoT into telecommunication networks can significantly improve management and overall efficiency. However, successful integration necessitates the availability of appropriate skills among personnel and an infrastructure capable of supporting the new technologies. Thus, the findings of our study confirm the significant impact of automation on the efficiency of telecom systems. They open new horizons for further research and emphasise the importance of an integrated approach to the implementation of new technologies. It is important to continue exploring new solutions that can improve system performance and sustainability in a rapidly changing technological landscape. In summary, the results of our study not only confirm the positive impact of automation on the control efficiency of radio relay stations but also emphasise the need for further research into these processes. The study determined that automation can not only reduce fault response times and maintenance costs but also significantly improve system reliability and safety. This in turn opens up new prospects for the introduction of innovative technologies such as IoT and AI, which can significantly improve the management of telecoms networks.

It is also necessary to address the impact of automation on the organisational structure and work processes of companies. Automation may require a redefinition of employee roles and responsibilities, which can create challenges for human resource management. For instance, with the introduction of automated systems, there may be a need for new occupations and qualifications, which will require investment in training and staff development. Z.G. Khanzad & A.A. Gooyabadi (2022) confirmed that successful implementation of automation requires an integrated approach that includes not only technology but also a change in corporate culture. Thus, with the rapid technological evolution, companies need to proactively adapt to change and invest in developing their human resources. Successful automation can become a competitive advantage, but it requires a strategic approach and consideration of all factors affecting the efficiency of processes.

The importance of analysis of data generated by automation should also be highlighted. Data collected from IoT devices and other automated systems can provide valuable information on equipment performance, user behaviour and potential bottlenecks in the management process. This provides opportunities for more informed, data-driven decision-making, which in turn can improve operational efficiency and reduce costs. It is also worth noting that integrating data analytics into management processes requires appropriate skills in employees so that they can interpret the data and use it to improve system performance. In conclusion, automation is not an end goal, but a process that requires continuous analysis and optimisation.

CONCLUSIONS

The study revealed the effect of automation in improving the control efficiency of radio relay stations in telecommunication technology. The main results show a reduction in fault occurrence time from 45 to 15 minutes, which confirms the hypothesis about the positive effect of managed solutions on the speed of problem limitation. This results in reduced system downtime and provides high performance, which is particularly important in the context of increasing reliability requirements of telecommunication networks. In addition, the study showed that automation reduces maintenance costs by 50%, from USD 6000 to USD 3000, by reducing manual maintenance costs and improving system reliability. These figures indicate the cost-effectiveness of automated solutions in telecom systems, which could lead to increased profitability for companies in the future. It was also found that system reliability increased by 13%. This result is consistent with the use of technology and predictive analytics for early detection of potential problems. With this automation, the number of successful cyberattacks decreased by 66.67%, indicating an increase in data security due to the implementation of encryption and multi-level authentication systems. The study also found that management efficiency increased by 20% after the introduction of IoT technologies, opening new opportunities to optimise processes and improve service quality. Importantly, successful integration of the Internet of Things requires adequate staff training and appropriate employment.

However, it is worth noting the limitations of the study, in particular, the need for significant initial investment in automation and staff training, which can ensure that a company develops new technologies. The study also does not cover all aspects of automation and therefore requires further research. Based on the findings, it is recommended to research to analyse the cost-effectiveness of automation, as well as to study the impact of new technologies on organisational culture and work processes in telecommunications companies. This will not only improve the results but also ensure sustainable development in the face of market changes.

Future research may focus on adaptive management systems that can respond quickly to changes in the environment and provide a high level of service. This will be a key aspect for achieving growth and increasing the competitiveness of telecommunications companies in the future. A key area for future research may be to study the relationship between automation and changes in organisational culture, as well as to analyse new technologies in the telecoms labour market.

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CONFLICT OF INTEREST

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Аналіз системи управління радіорелейними станціями з використанням IT-технологій

Анотація. Дослідження зосереджене на теоретичному аналізі систем керування радіорелейними станціями, що використовують сучасні інформаційні технології. Основною метою роботи стало виявлення потенціалу підвищення продуктивності, надійності та економічної ефективності таких систем. У рамках аналізу розглядалися передові сенсорні технології, алгоритми автоматизації та методи моніторингу, які могли істотно знизити витрати на обслуговування і прискорити реагування на несправності. Розглянуто ключові аспекти, що впливають на продуктивність радіорелейних станцій, включно з впливом кліматичних умов і різними сценаріями експлуатації. Підкреслено значущість інтеграції автоматизації для підвищення надійності роботи систем і зниження впливу людського фактору. Акцентовано увагу на відповідності запропонованих рішень міжнародним стандартам радіорелейного зв'язку, що спростило інтеграцію з наявними мережами та можливість майбутньої модернізації. Результати дослідження обґрунтували необхідність автоматизації радіорелейних систем і створили теоретичну базу для їхнього подальшого розвитку та вдосконалення, що відкрило нові можливості для поліпшення експлуатаційних характеристик і підвищення стійкості до потенційних збоїв. Проаналізовано впровадження нових підходів до управління даними та аналізу, що давало змогу оперативно реагувати на зміни в умовах експлуатації та оптимізувати ресурси. Ці аспекти забезпечили конкурентні переваги в умовах швидко мінливого середовища телекомунікаційних технологій, підкреслюючи важливість гнучкості та адаптивності систем для ефективної роботи. У підсумку, вивчення теоретичних основ автоматизації могло стати основою для практичних рекомендацій щодо впровадження інноваційних технологій в управління радіорелейними станціями

Ключові слова: автоматизація зв'язку; сенсорні модулі; машинне навчання; віддалений моніторинг; підвищення надійності; економічна ефективність

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Innovative technologies to improve energy efficiency and security of military facilities

Abstract. The purpose of this study was to analyse the potential of innovative solutions for optimising energy processes and strengthening security systems at military facilities. The study analysed scientific papers, reports, and publications on energy and cyber technologies, using a comparative analysis of approaches to the implementation of renewable energy sources, intelligent control systems and automated technologies at military facilities. The findings confirmed that renewable energy sources (solar panels, wind turbines) reduce dependence on fossil fuels and increase the autonomy of bases. Intelligent energy management systems optimise costs and increase resource efficiency. Microgrids were found to provide a stable power supply even in case of outages. Protecting critical infrastructure using multi-level cybersecurity systems and artificial intelligence significantly reduces the risk of attacks. It was emphasised that microgrids reduce the risk of power outages during crises or cyberattacks, allowing for a quick switch to backup energy sources. Innovative insulation materials and energy-efficient equipment reduce operating costs and improve working conditions for staff. Cyber defence of critical energy systems at military facilities includes multi-level protocols, monitoring of network

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activity and encryption technologies to prevent cyber-attacks. The use of artificial intelligence to analyse threats allows for prompt detection and response to anomalies. It was proved that innovative technologies are key to ensuring energy independence, security, and efficiency of military facilities. The findings of this study can be used to optimise energy consumption and increase the level of autonomy of military bases, which will ensure the stability of the facilities' operation even in difficult conditions or in cases of lack of access to external energy sources

Keywords: renewable energy sources; microgrids; cybersecurity; autonomous energy storage systems; critical infrastructure protection; artificial intelligence

INTRODUCTION

Military bases and infrastructure facilities often operate in challenging environments with limited access to conventional energy sources, requiring the introduction of renewable energy sources such as solar panels and wind turbines, as well as energy storage systems to ensure continuous operation. Energy autonomy is a significant factor in war zones, where the stability of external grids can be disrupted. Innovative technologies can not only reduce dependence on external energy sources but also reduce the cost of energy transportation, which is critical for military operations. Furthermore, the introduction of intelligent energy management systems helps to improve energy efficiency, reduce costs, and increase the battery life of military facilities.

Particular attention should be paid to the cybersecurity of energy systems, as critical military facilities can be targeted by cyberattacks that can disrupt energy infrastructure. The development of secure control systems is a key aspect of security. Thus, the study and implementation of innovative technologies for energy efficiency and security will increase the operational readiness of military facilities, their resilience to external threats and reduce environmental impact, which is critical in the context of current challenges.

T. Vasylieva *et al*. (2021) substantiated the need for innovation to improve the efficiency of Ukraine's energy sector management, especially in the context of the transition to a carbon-neutral economy. The researchers emphasised the significance of a state strategy to attract investment in green technologies and promote energy-saving behaviour. While T. Vasylieva *et al*. focused on the national level, K.-H. Wang *et al*. (2021) and L. Zhang *et al*. (2021) covered the international aspect, examining the relationship between oil, CO_2 emissions, and military spending in importing countries. The findings of K.-H. Wang *et al*. showed cointegration in China, India, and Italy, which is explained by economic growth, high CO_2 emissions, and dependence on oil. In the United States, France, and other countries, this connection is absent due to military strategies and energy policies. The researchers recommended diversifying oil supplies, investing in military research, and developing renewable energy sources to reduce dependence on oil and CO_2.

P. Żuk & P. Żuk (2022) analysed the impact of political conflicts on energy policy, emphasising the significance of diversifying energy sources. The researchers concluded that conflicts encourage countries to make policy changes, such as diversifying energy sources and developing alternative sources, to reduce dependence on imports. A. Azzuni & C. Breyer (2021) proposed a numerical index to assess energy security, which allows quantifying its level in different countries. The findings showed that Germany and the United States have the highest energy security scores, while the Central African Republic and Turkmenistan have the lowest. The researchers concluded that to improve energy security, countries should choose approaches that are suitable to their conditions.

The methodological approach presented by L. Zhang *et al*. (2021) was distinguished by its complexity, as it included seven dimensions of energy security and 28 indicators using Fuzzy AHP and GRA-TOPSIS. The study found that energy security is a multidimensional concept, and it is essential to consider technological, environmental, social, and political aspects to strengthen it. The study by L. Zhang *et al*. was global in nature, while S. Malik *et al*. (2022) focused on local problems and proposed solutions adapted to the specifics of the region. The researchers analysed Pakistan's energy security by analysing it from four aspects (availability, applicability, acceptability, affordability) in the period from 2011 to 2017. The study revealed that despite investments in energy infrastructure, Pakistan is still energy insecure. The researchers recommended the active implementation of green energy solutions such as solar energy, smart meters, and building insulation standards to improve the situation.

M. Krelina (2021) investigated military applications of quantum technologies and their potential effects on defence and security. The conclusions stated that quantum technologies could considerably improve the efficiency and accuracy of military operations, leading to new military strategies and ethics. The report provides an overview of quantum technologies, estimates their timeline for implementation, and describes their application in various areas of warfare, including land, air, space, electronic, cyber, and undersea warfare.

The purpose of this study was to analyse modern technological innovations that can help optimise energy use and improve security measures at military facilities. The objectives of the study were to consider technologies for improving the energy efficiency of military facilities, review innovative security solutions, and examples of the implementation of such technologies in global military structures, and make recommendations for future use.

MATERIALS AND METHODS

The theoretical part of the study was based on a series of scientific papers, reports, and publications describing the use of the latest technologies in the military sphere (Table 1). To consider energy aspects, the study used publications on energy technologies, as well as works on energy efficiency strategies at military facilities. Documents related to automation and intelligent control systems at military facilities were used to analyse the effectiveness of such technologies in the context of military infrastructure. Proceeding from these sources, key technologies that can contribute to energy efficiency and security were identified.

Table 1. Classification of sources and their use in the study

Source type	Focus	Source example	Use in the study
Scientific articles	Analysis of innovative technologies, energy efficiency, cybersecurity	T. Vasylieva *et al.* (2021) – implementation of "green" technologies; L. Zhang *et al.* (2021) – energy security assessment	Sources were used for theoretical analysis of innovative technologies, determination of multidimensional approaches to assessing energy security and the role of microgrids in crisis conditions
Reports of international organisations	Implementation of renewable energy sources, integration of microgrids, technology development	International Renewable Energy Agency (2024) – renewable energy; Defense Advanced Research Projects Agency (2023) – artificial intelligence; NATO (2024) reports – cybersecurity of military facilities	Sources were used to analyse practical examples of energy solutions, cyber defence of critical infrastructures, and the implementation of microgrids at military facilities
Regulations	Regulation of energy technologies, energy efficiency standards, cybersecurity	Laws of the USA (Clover *et al.*, 2024) and Canada (Government of Canada, 2020), European directives (European Defence Agency, 2024) on energy efficiency	These sources helped to formulate recommendations for the integration of technologies in line with international safety norms and standards
Practical cases	Implementation of energy and security solutions at military facilities	Fort Bliss base (USA) – microgrids; military facilities in Germany – insulation materials; base in Canada – wind turbines	Illustrations of the implementation of the latest technologies in real-world conditions helped to confirm the effectiveness of the proposed approaches

Note: NATO – North Atlantic Treaty Organization
Source: compiled by the authors

To determine the effectiveness of the use of innovative technologies in military facilities, a series of reports and publications on the use of alternative energy sources and intelligent systems in the military sphere were analysed. This included the reports of international organisations such as International Renewable Energy Agency (2024), Defense Advanced Research Projects Agency (2023), NATO (2024), as well as national institutions in the United States (Clover *et al.*, 2024), Canada (Government of Canada, 2020), and Europe (European Defence Agency, 2024). The study also reviewed relevant regulations and programmes that promote the development of energy technologies at military bases.

One of the principal research methods was a comparison of different approaches to ensuring energy efficiency and security of military facilities in different countries. The comparative analysis included the study of examples of the use of solar panels, wind turbines, hydrogen fuel cells, as well as cybersecurity technologies and automated systems at bases in the United States, Canada, the United Kingdom (Government of the..., 2024), and Germany. This helped not only to understand which technologies are the most effective, but also to identify the key factors influencing their implementation.

RESULTS

Energy efficiency has become a key element in the design and operation of modern military facilities. Apart from reducing operating costs, it ensures independence from unstable fuel supplies and reduces the need for regular deliveries, which is especially significant for facilities in remote and dangerous areas. According to International Renewable Energy Agency (2024) reports, the use of renewable energy sources in military facilities can provide a sustainable, independent energy supply, and reduce the risks for personnel involved in the supply of energy resources.

Modern military bases are increasingly implementing solar panels as the main or additional source of energy (Katalenich & Jacobson, 2022). Renewable sources not only reduce dependence on conventional fuels, but also ensure the sustainability of energy supply in conditions of remoteness or limited access to resources. Countries such as the United States are actively using solar panels at military bases, with a study by K. Belousova (2022) showing that solar energy projects substantially reduce costs and increase the autonomy of military facilities.

Wind turbines are used to provide additional energy supply, especially at military bases located in areas with stable wind flows. Wind turbines, as part of a combined energy system, reduce the overall consumption of conventional energy resources (Kanwal *et al.*, 2022). The principle of operation of a microgrid with the integration of wind turbines is presented below (Fig. 1).

The use of insulating materials and energy-efficient coatings can reduce heat or cold loss, providing comfortable conditions for personnel and equipment. Effective insulation reduces the need for air conditioning or heating, which is essential for energy savings, especially in large military facilities (Wen *et al.*, 2021). Intelligent lighting systems with automatic control can save energy by using motion and light level sensors. This reduces the load on the power grid and increases the efficiency of resource use.

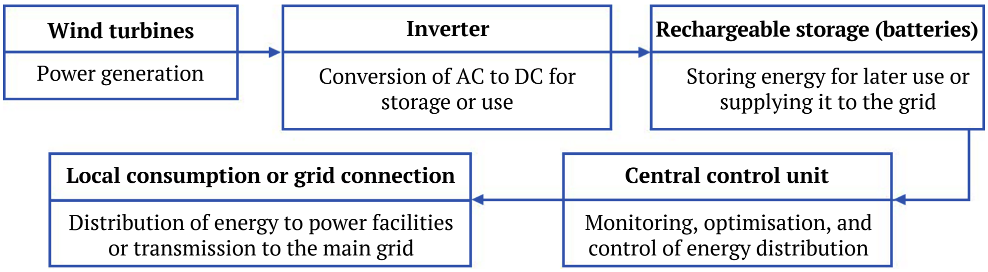

Figure 1. Operation of a microgrid with the integration of wind turbines
Source: compiled by the authors based on O. Saritas & S. Burmaoglu (2016)

Intelligent systems based on the Internet of Things (IoT) allow monitoring and optimising the use of electricity at military facilities (Prozuments *et al*., 2019). They collect data on energy consumption, automatically detect costs, and allow systems to be adjusted to reduce consumption. Microgrids provide energy storage and distribution within the facility, optimising consumption, and providing flexible management of energy flows. They can operate autonomously in case of a loss of the primary energy source, which is especially useful for military facilities located in areas with unstable energy supplies. Such systems allow creating autonomous energy networks that can operate independently of the central power grid (Shah *et al*., 2022). In case of an emergency, microgrids can automatically switch to backup energy sources, ensuring that the facility's energy needs are met without interruption. Although the prohibitive cost of investment and the need for qualified personnel to maintain these systems are major challenges, their use at remote military bases provides the necessary energy independence and increases resilience to external threats.

The use of artificial intelligence technologies to process and analyse video surveillance data allows for the rapid detection of potential threats. Thanks to machine learning algorithms, systems can analyse the behaviour of people and vehicles in real time, recognise abnormal actions, and immediately alert security. For example, Defense Advanced Research Projects Agency (2023) research suggests that the use of artificial intelligence video analytics at military facilities substantially increases the efficiency and speed of response to threats.

Intelligent sensors and artificial intelligence systems allow detecting suspicious activity on the territory of military facilities and sending real-time notifications to security services. For instance, cameras with built-in artificial intelligence algorithms can recognise anomalous activities, such as unauthorised movement or intrusion. The US is already actively using such systems at military bases, which reduces the need for constant physical patrols (Clover *et al*., 2024). This considerably increases the speed of response to threats and reduces the need for additional forces to protect facilities.

Modern sensor systems can detect any movement on the territory of an object, even at night or in harsh weather conditions. Infrared barriers are installed around important facilities and are triggered by any crossing of the perimeter (Huang *et al*., 2021). Such systems are widely used in NATO (2024) military structures to strengthen the protection of bases and warehouses. With the growing threat of cyberattacks, the protection of information networks and databases has become a priority for military facilities. Military structures are implementing multi-level security protocols, encryption, and artificial intelligence-based network activity monitoring technologies. This allows them to quickly detect unauthorised access attempts (Mittal & Davidson, 2020).

Critical energy systems of military facilities are also subject to protection from cyberattacks, as their damage can lead to severe disruptions (Hemmati & Rahmani, 2022). In case of an emergency, such as a failure of the main power source or a physical attack on the facility, military facilities must be able to quickly switch to backup or autonomous power sources. For this purpose, generators, high-capacity batteries, and energy storage systems are used. Military organisations in different countries are actively implementing modern technologies to ensure energy efficiency and security. This allows not only to reduce operating costs but also to increase the autonomy and security of facilities from external threats. Below are a few examples from different countries that have already succeeded in this area (Table 2).

Table 2. Technologies and use examples

Country	Technology	Use example	Outcomes and advantages
USA	Solar panels and microgrids	The Fort Bliss military base uses a microgrid with solar panels and batteries for energy storage	Improved autonomy of the base and reduced electricity costs by 20-25%
Canada	Wind turbines and energy management system	The base in northern Canada has wind turbines and a system for monitoring and optimising energy consumption	Reduction of dependence on traditional fuels and cost savings on transportation of resources
United Kingdom	Cybersecurity and backup power systems	Use of multi-level cybersecurity protocols and autonomous energy storage systems at key facilities	Increased resilience to cyber-attacks and ensure continuity of operations even during attacks

Continued Table 2.

Country	Technology	Use example	Outcomes and advantages
Germany	Energy-saving lighting and intelligent sensors	LED lighting with motion sensors and automatic light control is installed at military facilities	Reduced lighting costs by 30-40% and reduced electricity consumption
Japan	Autonomous microgrids and hydrogen fuel cell generators	Implementation of microgrids powered by hydrogen fuel cells to ensure energy independence on the islands	Provision of facilities in remote areas with an independent and environmentally friendly source of energy

Note: LED – light-emitting diode
Source: compiled by the authors based on Government of Canada (2020), L. Clover *et al*. (2024), European Defence Agency (2024), Government of the United Kingdom (2024), Y. Tsuji (2024)

Military bases that use alternative energy sources, microgrids, and modern control systems can considerably reduce operating costs and ensure the resilience of facilities even in case of emergencies. These innovations have proven to be effective and have become a vital aspect in improving the security and energy independence of military facilities (Tutak & Brodny, 2022). Furthermore, due to the reduced environmental impact from the use of clean energy sources, such solutions are supported by environmental programmes.

The use of renewable energy sources at military facilities is becoming increasingly popular, as it not only reduces dependence on fossil fuels but also increases the autonomy of the facilities (Yaghoubi *et al*., 2022). Military bases located in remote regions face logistical challenges in terms of regular fuel supply, which can be dangerous or costly. Solar panels installed on buildings and special stations provide a stable supply of electricity even in the absence of a connection to the central grid (Shahini *et al*., 2024). Such units are available in the US and the UK, where they cover a major portion of the energy needs of bases, reducing fuel costs and minimising the risks associated with fuel transportation.

Energy management systems based on the IoT enable detailed monitoring of all electricity consumers at facilities, ensuring optimised use of resources (Affum *et al*., 2021). Intelligent sensors installed on electrical appliances and buildings provide information on consumption levels, allowing unused devices to be automatically switched off or power to be reduced during off-peak periods. For example, according to research.

New insulation materials and coatings for buildings at military facilities help reduce heat and cold loss, which can greatly reduce heating and air conditioning costs. For example, NATO bases in Northern Europe are actively using modern thermal insulation materials that provide protection against harsh climatic conditions and help keep buildings warm in winter (Nuchturee *et al*., 2020). This not only creates a comfortable environment for personnel, but also reduces the energy load on the base, providing great resource savings and reducing environmental impact.

Protecting energy systems from cyber threats is a critical part of the security strategy of military facilities, as cyber-attacks can lead to a complete power outage and disruption of critical infrastructures (Sandri *et al*., 2020). Military facilities are implementing multi-level security systems, including encryption, continuous monitoring of activity, and automatic detection of suspicious activity using artificial intelligence. For example, NATO is actively researching the cybersecurity of energy systems, including microgrids, to ensure continuous operation even in case of cyber-attacks (Ige *et al*., 2024).

Autonomous energy storage systems, such as generators, large batteries, or hydrogen fuel cells, allow military facilities to stay energy independent for a prolonged time. Hydrogen fuel cells, for instance, can provide autonomous power for facilities for several days, which is crucial for military bases located in remote regions or in unstable situations. For example, military bases in Japan use hydrogen fuel cells to ensure continuous operation even during crises, which provides a strong advantage in terms of energy sustainability (Tsuji, 2024). As indicated in Table 3, various autonomous energy storage technologies have already been applied in practice, demonstrating their effectiveness in ensuring energy autonomy in crisis conditions.

Table 3. Technologies and use examples

Technology	Country	Use example	Outcomes and advantages
Renewable energy sources	USA	Use of solar panels on military bases for basic/ additional energy supply	Reduced dependence on fossil fuels, increased autonomy of bases, reduced operating costs
Intelligent energy management systems	United Kingdom	Installation of IoT sensors to monitor and optimise energy consumption	Optimisation of energy consumption by 15-20%, prevention of overloads, and increased resource efficiency
Microgrids	USA	Use of an autonomous microgrid with solar panels and batteries based on Fort Bliss	Increase facility resilience, ensure uninterrupted power supply in case of accidents or cyber threats, and save money
Modern insulation materials	Germany	Use of thermal insulation materials in military buildings to reduce heat loss	Reduced heating and air conditioning costs, increased energy efficiency, improved staff comfort
Cybersecurity of energy systems	NATO	Implementation of network activity monitoring systems based on artificial intelligence	Protection against cyber-attacks, ensuring the security of energy systems, reducing the risk of energy supply loss

Continued Table 3.

Technology	Country	Use example	Outcomes and advantages
Autonomous energy storage systems	Japan	Use of hydrogen fuel cells as a backup power source at remote military bases	Provision of energy independence, possibility of autonomous operation for several days, reduction of costs for imported fuel
Artificial intelligence and sensors for security	USA	Using artificial intelligence analysis of video surveillance to recognise abnormal behaviour at facilities	Rapid response to threats, increased efficiency of the security service, reduced need for physical patrols
Energy-saving lighting	Germany	Installation of LED lighting with automatic light intensity control	Reduced electricity consumption by 30-40%, improved lighting efficiency, reduced operating costs

Source: compiled by the authors based on Government of Canada (2020), L. Clover *et al*. (2024), European Defence Agency (2024), Government of the United Kingdom (2024), Y. Tsuji (2024)

Since modern technology is developing rapidly, many military organisations recognise the potential of such solutions. However, a series of technical, economic, and organisational aspects must be considered for their successful implementation. Solar panels and wind turbines are environmentally friendly and cost-effective sources of energy in the long term (Szafraniec *et al*., 2021). They can provide energy to military bases, reducing dependence on fossil fuels, which is especially significant for remote military facilities. However, these systems require extensive upfront investment, and their efficiency can be affected by erratic weather conditions. To increase the efficiency of such systems, supplementary energy storage is required. The combined use of solar and wind energy together with microgrids and energy storage can solve these problems, as is already the case in the US, Canada, and Germany.

The use of heat-insulating materials can greatly reduce heat loss, which decreases the cost of heating and air conditioning (Serdyuk *et al*., 2024). Energy-efficient lighting, such as LED lamps, helps to save energy. However, retrofitting existing military facilities can be challenging due to their specific structure and the prohibitive cost of some modern materials. In the long-term, investments in such materials are cost-effective, as they contribute to sustainable energy savings. Protecting critical energy infrastructures from cyber threats is becoming increasingly critical. Integration of cyber defence technologies reduces the risk of attacks but requires constant security updates and integration with other security systems, which requires extensive financial and technical resources (Metelskyi & Kravchuk, 2023). Implementing multi-level security systems, encryption, real-time activity monitoring, and the use of artificial intelligence to detect anomalies can greatly improve security.

Intelligent monitoring systems and artificial intelligence can quickly detect potential threats by analysing data from video cameras and sensors, which increases the efficiency of facility security. However, they require qualified personnel to process large amounts of data and store confidential information. Sensor systems and infrared barriers also play an essential role in detecting movement at facilities in difficult conditions or at night. While such systems can be expensive to deploy over large areas, the combined use of sensors and surveillance cameras with artificial intelligence analytics can reduce the probability of false alarms. The introduction of innovative technologies at military facilities increases their autonomy, reduces dependence on conventional fuels, and reduces risks to personnel. It also increases the level of energy independence and security, enabling an effective response to challenges and ensuring that military facilities are prepared to operate in emergency conditions.

For the successful implementation of such technologies, it is recommended to invest in research and development, continuously improve energy saving technologies and security systems, develop human resources through staff training, cooperate with the private sector to develop and implement high-tech projects, and regularly monitor the effectiveness of the implemented technologies to adjust the strategy and improve efficiency. Thus, the integration of the latest technologies at military facilities is a necessary step to ensure energy sustainability, operational readiness, and national security in the face of emerging challenges and threats.

DISCUSSION

This study focused on the analysis of innovative technologies that improve the energy efficiency and security of military facilities, which are increasingly vulnerable to cyber and physical attacks. The key findings of the study revealed that the introduction of renewable energy sources, such as solar panels and wind turbines, considerably increases the energy autonomy of military facilities. In addition, the use of innovative insulation materials and energy-efficient lighting systems helps to reduce operating costs and provides comfortable conditions for personnel.

Intelligent energy management systems based on IoT help optimise resource use and reduce energy consumption (Boiko *et al*., 2023). A crucial aspect of the study is to improve the cybersecurity of military facilities. The use of artificial intelligence to monitor and analyse video data, as well as modern sensor systems for motion detection and perimeter control, ensures prompt detection of potential threats. Multi-level cyber defence protocols and autonomous energy storage systems increase the resilience of facilities to attacks and ensure their operational readiness even in crisis situations.

A. Soni (2019) investigated potential major changes in the way the US military uses energy technologies and their effects on national security. The energy chain was used to analyse energy technologies – production, storage, transmission, and use of energy. The lethality-survivability-mobility triangle was used to assess deployed technologies to identify potential locations and methods for strategic change. The study provided suggestions for significant research areas and organisational aspects of energy technology procurement for the US military. The current study confirmed the significance of these aspects, specifically the approach to autonomous energy systems, but focused more on their impact on fixed military facilities, while A. Soni (2019) focused on the strategic use of technology in mobile military operations.

O. Saritas & S. Burmaoglu (2016) analysed the growing energy needs in military operations due to changes in warfare. The study focused on the evolution of energy requirements from World War II to Operation Desert Storm in 1991, and on to modern technologies that include night vision, laser targeting, advanced sensing, and communications capabilities, as well as drones and robotics. Using trend analysis, technology mining, and scientometrics, the study developed future scenarios and a strategic roadmap for priority technology areas in military energy research and development. The current study confirmed the trend of increasing energy requirements due to the growing dependence on technologies such as IoT, drones, and laser systems. At the same time, the present study added an analysis of the impact of microgrids and energy management systems that increase the energy autonomy of modern military bases.

In the study by M.N. Norrrahim *et al*. (2021), nanocellulose also demonstrated great functionality and potential for many applications, including body armour, materials with fire-resistant properties, and filtration elements, which can reduce dependence on conventional materials and increase the efficiency of military facilities. Both studies were aimed at developing solutions to improve security. The use of nanocellulose in military materials can improve protection due to its mechanical and heat-resistant properties. The conducted study addressed cybersecurity and the protection of energy systems at military facilities, which is also significant for the protection of critical infrastructure. In the current study, the author agreed that innovative materials play a key role in enhancing protection but focused on the integration of the latest cybersecurity technologies to protect energy systems, which is critical in the modern military context.

The study by A.Z. Isiksal (2021) on the impact of military spending and renewable energy consumption on CO_2 emissions has much in common with the study on the energy efficiency of military facilities, particularly in the context of reducing the carbon footprint and increasing the energy independence of military structures. The study on military spending and CO_2 emissions indicates that increased military spending contributes to increased CO_2 emissions, confirming the "treadmill of destruction" hypothesis. This hypothesis states that an increase in defence spending is accompanied by an increase in pollution. The study focuses on improving energy efficiency and reducing environmental impact through the introduction of modern technologies (solar panels, wind turbines, microgrids). The introduction of renewable energy sources is significant for reducing the carbon footprint, promoting environmental sustainability, and ensuring energy autonomy of military facilities. The use of solar panels and wind turbines minimises dependence on fossil fuels and optimises energy costs (Qawaqzeh *et al.*, 2020).

Overall, the study demonstrated that the integration of innovative technologies is necessary to improve the energy efficiency and security of military facilities. It is recommended to continue the development and implementation of these technologies, invest in research, personnel training, and cooperate with the private sector to implement high-tech projects.

CONCLUSIONS

Innovative technologies to improve the energy efficiency and security of military facilities provide major benefits, including energy independence and resilience, efficient resource management, and enhanced cyber security. The introduction of renewable energy sources, such as solar panels, wind turbines and hydrogen fuel cells, makes military facilities less dependent on external energy sources. This reduces the need for a constant supply of fuel and increases autonomy, especially for remote facilities. Energy management systems and microgrids optimise the use of resources and enable rapid response to threats or energy disruptions. Microgrids ensure a stable power supply, even in case of an outage in the central grid. As military facilities are becoming major targets of cyber-attacks, multi-level defence systems and intelligent monitoring systems are essential to ensure the security of critical infrastructures.

Considering the growing significance of energy efficiency and security of military facilities, it is recommended to expand the use of renewable energy sources, develop autonomous energy systems, improve cyber defence, and expand the use of energy-saving technologies. The introduction of alternative energy sources should be continued, especially in remote bases and facilities where it may be challenging to ensure a constant supply of fuel. The use of autonomous microgrids maintains access to electricity even during emergencies, reducing the risk of power outages and providing flexible management of energy flows. Continuous improvement of cybersecurity is critical to protecting information and energy systems. It is vital to develop systems with early detection of threats and backup infrastructures. Military facilities should be equipped with intelligent energy monitoring systems and energy-efficient equipment (e.g., LED lighting with motion sensors and automatic temperature control systems).

Further research could be aimed at expanding the analysis of the effectiveness of introducing microgrids and renewable energy sources at military facilities in diverse climatic conditions. Particular attention should be paid to the effects of innovative technologies on reducing operating costs and increasing energy autonomy in extreme environments. Another promising area is the development of cybersecurity systems to protect the energy infrastructures of military bases. In this context, it is essential to evaluate the use of artificial intelligence for early threat detection and automated crisis management.

The development of new insulating materials and energy-efficient systems could be another area of research, particularly in the context of reducing the environmental impact of military operations. Integration of these technologies with modern IoT solutions can considerably optimise energy processes. Further research could also focus on creating scalable and cost-effective microgrid models for small and medium-sized military bases, as well as assessing opportunities for cooperation with commercial entities to develop joint innovative projects.

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CONFLICT OF INTEREST

None.

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Інноваційні технології для підвищення енергоефективності та безпеки військових об'єктів

Анотація. Метою даного дослідження був аналіз потенціалу інноваційних рішень для оптимізації енергетичних процесів та посилення систем безпеки на військових об'єктах. В ході дослідження було проаналізовано наукові праці, звіти та публікації з питань енергетики та кібертехнологій, за допомогою порівняльного аналізу підходів до впровадження відновлюваних джерел енергії, інтелектуальних систем управління та автоматизованих технологій на військових об'єктах. Результати дослідження підтвердили, що відновлювані джерела енергії (сонячні панелі, вітрогенератори) зменшують залежність від викопних видів палива та підвищують автономність баз. Інтелектуальні системи управління енергією оптимізують витрати і підвищують ефективність використання ресурсів. Мікромережі забезпечують стабільне електропостачання навіть у разі відключень. Захист критичної інфраструктури з використанням багаторівневих систем кібербезпеки та штучного інтелекту значно знижує ризик атак. Було підкреслено, що мікромережі знижують ризик відключення електроенергії під час кризових ситуацій або кібератак, дозволяючи швидко переходити на резервні джерела енергії. Інноваційні ізоляційні матеріали та енергоефективне обладнання зменшують операційні витрати та покращують умови праці персоналу. Кіберзахист критичних енергетичних систем на військових об'єктах включає багаторівневі протоколи, моніторинг мережевої активності та технології шифрування для запобігання кібератакам. Використання штучного інтелекту для аналізу загроз дозволяє оперативно виявляти аномалії та реагувати на них. Доведено, що інноваційні технології є ключовими для забезпечення енергетичної незалежності, безпеки та ефективності військових об'єктів. Результати дослідження можуть бути використані для оптимізації енергоспоживання та підвищення рівня автономності військових баз, що забезпечить стабільність роботи об'єктів навіть у складних умовах або у випадках відсутності доступу до зовнішніх джерел енергії

Ключові слова: відновлювальні джерела енергії; мікромережі; кібербезпека; автономні системи накопичення енергії; захист критичної інфраструктури; штучний інтелект

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