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Research of the regulator of an expander-generator unit

Abstract. The relevance of research is determined by the tasks of increasing the efficiency of alternative and renewable energy power plants. The purpose of the work is to develop a method of coordinating the settings of the automatic excitation regulators and the speed of rotation of the rotor of the generator from the vortex installation of the expander-generator unit, which is part of the autonomous power consumption network. To achieve the goal, the methods of mathematical modelling in the MATLAB environment, physical modelling, processing of experimental data, theory of automatic control, theory of magnetic field, theory of electric machines, programming of microprocessor devices were used. Considering the need to expand the base of alternative energy sources, the task of controlling the energy plant for the utilization of excess pressure of gas transportation networks was considered. The study of the regulator of the expander-generator unit was based on a model reflecting the interaction of mechanical and electrical processes. A set of nonlinear differential equations corresponded to the description of these processes. Accurate consideration of nonlinearities of the considered control object complicates the implementation of the corresponding microprocessor control systems. Modelling is aimed at achieving a compromise between the required accuracy of object control and the possibilities of simplifying the object control structure. The use of experimental and datasheet data of the devices made it possible to evaluate the dynamics of turbine rotation and voltage generation, forming the factors for the untying of the control circuits. The use of MATLAB with the Lookup Table option made it possible to perform a multi-point linearization of the nonlinear description of the process, speeding up the modelling and adjustment of the regulator. This is important to

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coordinate the settings of the frequency control loops and the output voltage, given the trade-off between the speed of the regulator and the minimization of oscillations in the generation frequency. Based on the obtained results, a regulator of the expander-generator unit was developed, which ensures the stabilization of the initial parameters of the unit under the conditions of electrical load disturbances. In practice, the obtained data can be used in the integration of renewable energy sources into the general energy system through the optimization of the operation of generators

Keywords: vortex turbine; rotation frequency; coordination of settings; nonlinear model; synchronous generator; excitation regulator

INTRODUCTION

The perspective of any direction of improvement of power plants is determined by the design features of the main parameters embedded in it, as well as the current characteristics of the used working environments and automation tools. In the conditions of real operation, rapidly changing loads, work at fractions of power from the nominal, can cause a drop in the efficiency of the power plant.

One of such power plants is the expander-generator unit (EGU), which is used for monitoring the modes of technological equipment in gas distribution networks to provide energy. At the same time, there are no strict requirements for electricity generation modes, since electricity is obtained by utilizing excess gas pressure. At the same time, as the power consumption from the EGU increases, problems arise with the stability of the received energy parameters.

The relevance of research is determined by the tasks of assessing the energy efficiency of the operation of the EGU, as well as the prospects of building a system of coordination of local regulators, where deviations of the system parameters are involved in the regulation of the electricity generation process. Therefore, the prediction of the constant correspondence of the volumes of generated and consumed energy during the operation of the EGU determines the possibilities of effective operation of the installation. The need to establish compliance is related to variations in electricity consumption over time in the presence of disturbances in the parameters of the gas flow entering the turbine.

According to J. Bjork *et al.* (2022), the stabilization of the turbine rotation parameters of a power plant can be solved with the help of regulators built based on a turbine model of a certain type. At the same time, power generation specialists S. Rajamand (2020) continued research on improving the means of controlling electric generators. The author noted that the use of a synchronous generator and an adapted voltage drop system is important for maintaining the stable operation of microgrids with inverters. Control of a synchronous generator and modified drop allows for efficient regulation of frequency and voltage in microgrids incorporating inverter technologies. A. Mezerya & S. Pridvorov (2023) analyzed the qualitative indicators of the use of different types of generators at mini-hydroelectric power plants (HPP), focusing on the evaluation of efficiency, reliability and environmental impact indicators. Understanding these indicators helps in choosing the most appropriate type of generator for specific operating conditions and sustainability goals. In addition, this analysis provides insight into maintenance requirements and long-term operating costs, which are important for optimizing the overall efficiency of the mini HPP. The requirements for increasing the efficiency of generation mode control determine the use of more advanced algorithms for regulator settings. Given the value of the moment of inertia of the rotors of the vortex turbine (VT) and the EGU generator, respectively, the small time constant of the plant, adequate methods and algorithms for setting their regulators are necessary.

However, in the absence of correction of the values of gas consumption, which is utilized, according to changes in the electrical load of the network, the stabilization of the rotation of the generator does not ensure an increase in the efficiency of the EGU.

S.M. Baliuta *et al.* (2019) state that it is typical for turbine and generator control loops, “having common input control signals, not only to be designed but also tuned separately”. A natural step to overcome such a situation is the development of a unit for coordinating the functioning of the automatic excitation regulator (AER) and the automatic rotational speed regulator (ARSR). In a theoretical aspect, this approach can be classified as subordinate regulation, the parameters of which are synthesized in accordance with the established control quality criteria, in particular, the minimization of output voltage fluctuations during load drops. However, the analysis of the results of the regulator settings, conducted by H. Kulinchenko *et al.* (2023a) in mathematical modelling and experimental studies, shows that in addition to the dynamic parameters of the control circuits, the quality of regulation is affected by disturbances in the mechanical part of the EGU. Therefore, the simulation results are implemented with the help of additional SCADA-system automation tools of the EGU experimental installation.

O. Zenovych *et al.* (2020) concluded that the setting of AER and ARSR during the automation of experiments allows to significantly improve the quality of working out perturbations of the plant, however, the existing methods and algorithms for coordinating the settings of the regulators need improvement. Therefore, increasing the effectiveness of the EGU involves solving the following tasks:

1) development of additional primary parameter converters equipped with microprocessor interface means;

2) visualization of the parameters of the generation process in real time with the required rate of experimental data processing;

3) generalization of experimental data for their further application in the development of utilization units of the model and technical series of VT, and in the future, jet-vortex turbines.

Focusing on the adaptive control of VT, which ensures the stabilization of the generator voltage and the EGU rotational frequency during network load disturbances, the task arises to work out the interaction of the subsystems of the AER of the generator and the ARSR of the VT.

The purpose of the work was to develop a methodology for coordinating the settings of the automatic excitation regulators and the rotational speed of the rotor of the VT generator of the EGU installation, which is part of the power consumption network.

The scientific novelty of the work is evaluated by the prospects of using proven methods of controlling the turbines of utilization plants in alternative energy.

MATERIALS AND METHODS

With the use of MATLAB Simulink options, a mathematical model of the ECU was built, which reflected the results of the interaction of the mechanical and electrical parts of the unit. It contained the previously obtained VT model (Kulinchenko *et al.*, 2023b) and the mathematical model of the synchronous generator (SG) based on Park's equations. The Lookup Table (LUT) toolkit of the MATLAB Simulink environment was used to build the SG model. It made it possible to effectively display the nonlinear properties of the plant in the model by constructing LUT tables based on relevant experimental data.

The experiments were carried out according to the diagram in Figure 1, during which the parametric identification of the synchronous generator (SG) model was performed. As a result, the dependence of the value of the inductance of the excitation winding of the G-273 generator type on the excitation current $L_f=f(I_f)$ was obtained.

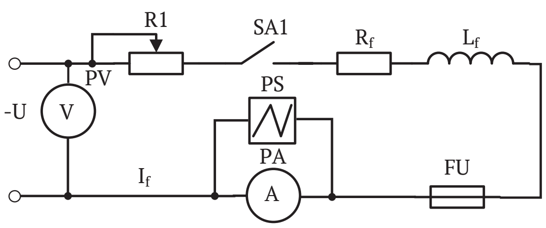

Figure 1. Diagram for estimating the time constants of the excitation winding

Note: R1 – variable resistor; SA1 – switch; R_f and L_f – active resistance and inductance of the SG excitation winding; PV – voltmeter; U – voltage; I_f – excitation current; PA – ammeter; PS – oscilloscope; FU – fuse

Source: created by the authors

The method of measuring the inductance of the excitation winding of the SG was based on the measurement of the time of the transient process of reaching a constant value of the excitation current I_f. The variation of the values of the excitation current of the winding was carried out by changing the values of the resistor *R*1. Registration of the transient process of the increase in current I_f was visualized with the help of a digital oscilloscope PS, which is turned on in parallel with the shunt of the ammeter PA. Thus, transient changes in voltage were matched to changes in the excitation current.

The value of the inductance L_f was determined based on the value of the time constant T_f, which was obtained from the registered transient process for different values of the excitation current I_f. The presence of values of the time constant T_f made it possible to construct the desired dependence $L_f=f(I_f)$ using the relation:

$$L_f=R_f{}^*T_f, \tag{1}$$

where R_f – previously measured active resistance of the SG excitation winding. The experimental dependence $L_f=f(I_f)$ obtained in this way was used in the construction of the *Lookup Table 1-D*, which is included in the diagram for modelling the excitation winding of the SG.

Also, within the parametric identification of the G-273 generator model, the experimental dependence of the electromotive force (EMF) of the generator on the excitation current I_f and the frequency ω_e, that is, the no-load characteristic (NLC) for different rotational frequencies of the source of mechanical energy (M), was obtained. For this purpose, experiments were carried out according to the diagram of Figure 2. It provided regulation of the current in the excitation winding F1-F2 and fixation of the frequency *n* of rotation of the SG using the frequency converter UZ. Discrete stepwise changes in the current in the excitation winding of the SG and the rotational frequency of the shaft of the installation made it possible to obtain a family of dependencies necessary for the creation of the *Lookup Table 2-D*, which is used in the general diagram of the SG model.

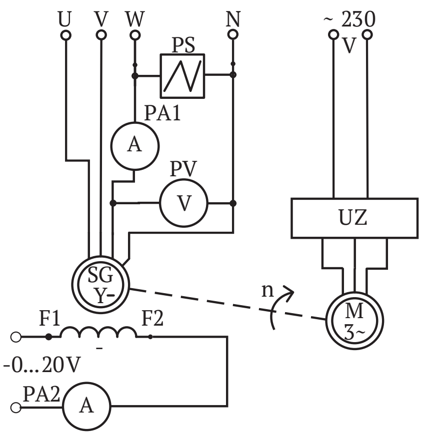

Figure 2. Diagram of the installation for obtaining experimental data on the estimation of SG parameters

Note: U, V, W and N – phases and neutral of a three-phase alternating current source; PS – oscilloscope; PA1, PA2 – ammeters; PV – voltmeter; UZ – frequency converter; SG – synchronous generator; M – asynchronous motor; F1-F2 – excitation winding of the synchronous generator

Source: created by the authors

The same circuit provided measurements of current and voltage values to calculate the resistances *Xd* and *Xq* by the method of small slip. The investigated generator SG, mechanically connected to the asynchronous motor M, was controlled by the frequency converter UZ feeding the motor M. In addition to measuring the voltage, the oscilloscope PS in the diagram of Figure 2 allowed to measure the frequency of the generated voltage. This provided consideration of the ratio of the rotor rotational frequency and the frequency of the generated voltage, which was calculated through the number of SG pole pairs. The measurement of the phase current of the armature winding, the values of which are necessary for the calculation of *Xd* and *Xq*, was carried out with the excitation winding F1-F2 open. The phases of the SG stator were fed from a separate low-voltage three-phase alternating current source. The frequency with which the source of mechanical energy M rotated was slightly different from the speed of rotation of the SG stator field.

The reactive resistance when connecting the stator winding according to the star connection is calculated as:

$$X_d = \frac{U_{Amax}}{I_{Amin}}, X_q = \frac{U_{Amin}}{I_{Amax}}, \tag{2}$$

where I_{Amin}, I_{Amax} – the minimum and maximum value of the phase current measured by the PA1 sensor; U_{Amin} (at I_{Amax}), U_{Amax} (at I_{Amin}) – minimum and maximum value of the phase voltage in the rotation mode measured by the PV sensor. The value of the calculated resistances (2) was used in building of the SG model.

Testing of the EGU regulator adjustment capabilities was carried out in the MATLAB Simulink environment on a mathematical model in the mode of changing the electrical load, which is considered a disturbance of the generation process. Setting the parameters of the EGU regulator was carried out using the MATLAB tool – *SISOTOOL*. This made it possible to carry out step-by-step sequential coordination of EGU circuits and proceed to the practical implementation of the regulator.

The adequacy of the developed model was assessed using an experimental setup (Vaneev *et al.*, 2019), presented in Figure 3. It was manufactured and is located at Sumy State University (Sumy, Ukraine) and includes a compressor as a source of compressed air, a gas regulator armature, turbine, electric generator, electric load, control and measuring devices.

Figure 3. Photo of the EGU experimental installation
Source: created by S.M. Vaneev *at al.* (2019)

Algorithmic software of the EGU controller is implemented on the means of a programmable logic controller (PLC) Simatic S7-300 CPU 314C-2DP (Siemens, Germany). The main software tools needed to build a SCADA-system and implement control algorithms include Step 7 and WinCC (Siemens, Germany).

RESULTS AND DISCUSSION

Development of the EGU model. The result of the interaction of the torque moment of the source of mechanical energy – VT, the aerodynamic torque moment of resistance of VT and the reaction torque moment of the generator to the electrical load is the factor that determines the parameters of rotation of VT/generator. Since this result forms the quality of electricity generation, in order to find out the configuration of the coordinator of the AER and ARSR settings, the structural diagram of the EGU model, shown in Figure 4, was considered.

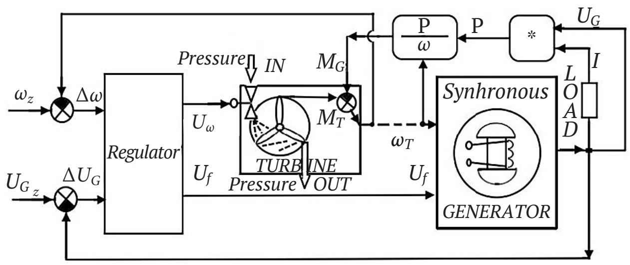

Figure 4. Structural diagram of the EGU model
Note: M_T – turbine torque moment; M_G – torque moment of reaction of the generator; ω_z, $\Delta\omega$ – turbine rotational frequency setpoint, its control error; ω_T – turbine rotational frequency; U_{Gz}, ΔU_G – generator voltage setpoint, its control error; U_f – excitation winding voltage; *P* – generator power; *I* – generator current
Source: created by the authors

In this diagram, as in any power plant, the main parameter of the regulated mode is the frequency of the generated alternating current. Since the deviation of this frequency from the nominal value is a parameter of the quality of electrical energy, the task of the EGU control system is to ensure the conditions for the normal functioning of the unit. It is the difficulties of cheap maintenance of the generation frequency that have so far inhibited the introduction of alternative energy installations to existing power grids.

The lack of opportunities to store energy and changes in electrical load cause continuous balancing of generated and consumed power. In the diagram (Fig. 4), this balancing is reflected by the interaction of the VT torque moment – M_T and the reaction torque moment of the synchronous generator M_G. The imbalance of moments (powers) causes changes in the frequency of the generated voltage. In the power plant, maintenance of the balance between generated and consumed power is achieved with the help of an automatic frequency and active power control system (AFAPCS). The AFAPCS system should perform the most economical frequency regulation.

The primary automatic control of the voltage frequency and active power of the SG is carried out in accordance with the tasks of controlling the rotational frequency. As a result of changing the position of the regulating valve, the pressure of the gas flow changes, which corrects changes in the frequency of rotation of the turbine, affecting the parameters of the generated gas power.

Another parameter that determines the modes of operation of the EGU is reliability and economy. Insufficient reliability of generation is manifested in disturbances of network voltage values over time. Voltage sags or surges, distortion of the voltage form are controlled with AER. However, control of the SG voltage is associated with a change in the rotational frequency, since in this case there is a redistribution of power between the mechanical and electrical components of the EGU. These components of the plant are related to each other through a controlled process, since frequency is the only parameter for SG and VT. Neglecting this connection, widespread practice focuses on the independent synthesis of AER and ARSR. However, considering the specifics of the operation of certain types of turbines leads to the need to use interconnected control of the turbine unit (Baliuta & Kuievda, 2017; Baliuta *et al.*, 2019). This approach involves the simultaneous control of the interaction of AER and ARSR, which makes it possible to build a system stabilizer, or coordinator of AER and ARSR settings.

The possibilities of synthesis of the excitation and rotational frequency control system, in accordance with the indicated control tasks, largely depend on the structure and complexity of the plant models used in the synthesis of the regulator.

Previous research by the authors showed that the nonlinear VT model can be represented by a family of transfer functions of the third order (Kulinchenko *et al.*, 2023b). These functions are built on the basis of linearization of the model at the selected operating points of the selected range of operation of the VT. The number of points in this range is determined by the requirements for the quality and stability of ARSR control.

Then, seeing the nonlinearity of the description of the SG functioning, the initial condition for the development of the AER for the EGU is the analysis of the nature of the nonlinearities of the SG model.

Mathematical model of SG. The key point of creating a SG model is a compromise between the necessary detail of its description and the level of reflection errors of this model. It is the excessive detailing of the plant model that complicates its use, hindering the development of simple adequate control criteria.

In addition, the analysis of electromagnetic processes occurring in the SG is associated with serious difficulties that depend on the order of the equations describing the model. In the MATLAB environment, the description of SG is provided by second-, third-, fifth-, or seventh-order models (Spoljaric *et al.*, 2010; Hrytsiuk *et al.*, 2017). Each of these models corresponds to the level of problems solved during modelling.

The system of differential equations, which is formed with respect to the phase currents and voltages of the SG, includes coefficients that change periodically when simulating the rotation of the rotor. These coefficients are formed from the values of inductances and mutual inductances (inductive resistances) of the SG windings. Magnetic asymmetry along the longitudinal (d) and transverse (q) axes is characteristic for the salient-pole design of the SG, since the air gap along these axes is different. This asymmetry is taken into account by the Blondel method, that is, by the method of two reactions of the magnetic field.

The use of two reactions, or components of the inductive resistance of the armature winding of a salient-pole SG in Park's equations (Melkebeek, 2018) makes it possible to simplify the modelling of the generation process. A practical step to significantly simplify the structure of the SG model is to consider the ratio of the time of transient processes in the armature circuits and the time of processes in the circuit of the SG excitation winding. Then, comparing the value of the time for the winding of the armature circuit with the time constant of the excitation winding, it can be assumed that the transient process is absent:

$$\frac{d\psi_d}{dt} = 0; \frac{d\psi_q}{dt} = 0, \tag{3}$$

where ψ_d, ψ_q – flux coupling of the armature according to the d q coordinates.

An additional factor for simplifying the SG model is the absence of a damping winding in the salient-pole SG of the G-273 type, which is used in the experimental EGU installation. Then the simplified system of Park's equations for the armature circuit will look like this (Zenovych *et al.*, 2020):

$$E = \omega * \psi_{fd},\ U_q = E - I_d * x_d,\ U_d = I_q * x_q, \tag{4}$$

where ψ_{fd} – flux coupling of the armature winding with the excitation flux Φ_f, which depends on the excitation current I_f; $x_d = \omega * L_d$; $x_q = \omega * L_q$ – inductive resistances of the SG armature winding along the d and q axes; I_d, I_q, U_d, U_q, – projections of currents and voltages on the d and q axis. These projections are related to physical quantities (voltage U_G and generator current I_G) as follows:

$$U_G = \sqrt{{U_d}^2 + {U_q}^2}, \quad I_G = \sqrt{{I_d}^2 + {I_q}^2}. \tag{5}$$

For the excitation winding, taking into account its resistance R_f and inductance L_f, the equation of the relationship between the voltage U_f and the current I_f of the excitation winding has the form:

$$U_f = I_f * R_f + \frac{d}{dt}(L_f I_f). \tag{6}$$

Working with the SG model, as with the plant model, involves the need to reflect the impact of disturbances on the output parameter of the SG – the output voltage U_G. The relationship between this voltage and the SG parameters is illustrated by a vector diagram based on the EMF of generator E (Fig. 5). This EMF is induced by the excitation winding flux, which, in turn, appears due to the excitation current I_f.

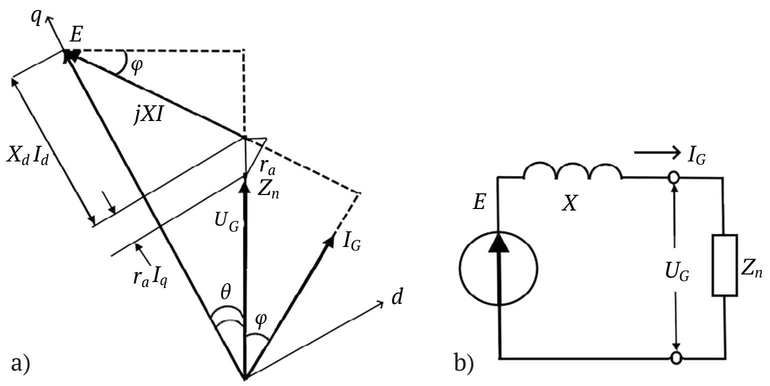

Figure 5. The vector diagram (a) and the substitution diagram of the salient-pole SG (b)
Note: a – vector diagram; b – equivalent substitution diagram; E – EMF of the generator, U_G – voltage generated by the SG, I_G– load current, Zn – complex resistance of the load, φ – load angle, θ – voltage U_G shift angle relative to the EMF of the generator E, X – complex resistance of the armature
Source: created by the authors

The analysis of the vector diagram in Figure 5 gives reason to write down the following equations in relation to the shift angle θ – the voltage U_G relative to the EMF of the generator E:

$$Eq = U * \cos\theta + x_d I_d + r_a I_q, \tag{7}$$

$$\theta = arctg\frac{x_q\cos\varphi - r_a sin\varphi}{z_n + r_a cos\varphi + x_q sin\varphi}. \tag{8}$$

In addition, we take into account that:

$$I_q = I_G * cos(\theta + \varphi),\ I_d = I_G * sin(\theta + \varphi),$$
$$I_G = U_G / Z_n \quad cos\varphi = R_n / Z_n \quad sin\varphi = x_n / Z_n, \tag{9}$$

where R_n, x_n – active and inductive load resistances; r_a, X – active and inductive resistance of the armature winding.

The angle φ characterizes the ratio of active R_n and reactive x_n components of the complex load resistance Z_n:

$$\varphi = arctg\frac{x_n}{R_n}. \tag{10}$$

Using the formulas of trigonometric transformations, the dependence of the EMF of the SG on the values of its parameters and load parameters was obtained:

$$E_q = \frac{U_G}{\sqrt{1+tg^2\theta}}(1 + \frac{1}{Z_n^2}[x_d(R_n * tg\theta + x_n) + r_a(R_n + x_n * tg\theta)]). \tag{11}$$

Taking expression (8) into account makes it possible to obtain a more compact equation of the output voltage of the SG and its EMF:

$$U_G = \frac{Z_n\sqrt{x_{qn}^2 + r_{an}^2}}{x_{dn} * x_{qn} + r_{an}^2}E_q, \tag{12}$$

where $x_{dn} = x_d + x_n$; $x_{qn} = x_q + x_n$; $r_{an} = r_a + R_n$. The next step of simplifying the model involves neglecting the value of the active resistance of the SG armature winding r_a, and constructing the equivalent electrical circuit of substitution shown in Figure 5b (Vasko, 2020). In this way, the basic nonlinear function of the $G = U_G/E$ model is obtained:

$$G = \frac{\sqrt{R_n^2 + x_n^2} * \sqrt{(x_q + x_n)^2 + R_n^2}}{(x_d + x_n) * (x_q + x_n) + R_n^2}, \tag{13}$$

which takes into account changes in the output voltage U_G depending on changes in the reactive resistance values of SG and load parameters.

The specificity of modelling the generation process is related to the need to reflect the influence of the change in the frequency of rotation of the SG on the mentioned changes in the resistance of the SG and perturbations of the load parameters. Using the MATLAB environment, according to equation (13), a diagram of the model of the nonlinear function G, shown in Figure 6, is created.

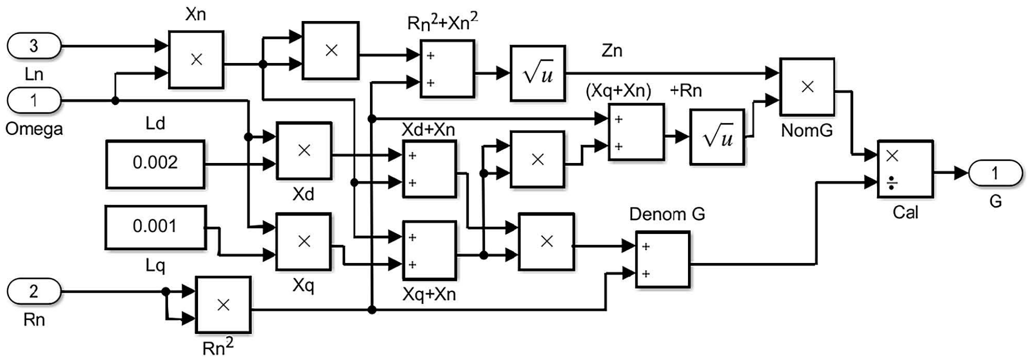

Figure 6. Diagram of modelling the nonlinear function *G*

Note: Xd, Xq and Ld, Lq – inductive resistances and inductances of the SG armature winding along the d and q axes; Rn, Xn and Zn – active, inductive and complex load resistances

Source: created by the authors

The theoretical means of SG modelling are based on the use of its datasheet data *Ld*, *Lq*, which are usually not available, and sometimes do not correspond to reality. A sufficient number of available practical methods, in particular the sliding method, allows us to experimentally determine the necessary data for modelling. At the same time, modern methods of estimating the resistances of the SG reaction, which are based on the complex SG model and its equivalent circuit (IEEE guide..., 2020), appear to be more promising in terms of the practical implementation of the model as a plant.

The general model of SG, in the form of plant, is supplemented by the equation of the excitation winding (6), which reflects the dynamics of the change in the current I_f under the influence of the voltage U_f on the excitation winding with resistance R_f and inductance L_f. As can be seen from equations (4), (6), (13), the nonlinearity of the entire SG model is formed not only by the nature of the relationships of the parameters of the electrical load of the generator, but also by the dependence of the complex resistances of the SG and magnetic fluxes on the characteristics of the magnetization curve.

The nonlinear functions representing the SG model cannot be solved by analytical methods at this stage, which creates problems for the next stages of modelling the EGU and its regulator. Therefore, a successful step, which allows using the Lookup Table (LUT) option of the MATLAB Simulink environment, based on stable modes of operation, to obtain a plant model (Gurskiy *et al.*, 2019).

The LUT tables are built on the basis of experimental data obtained during model adequacy evaluations on an experimental installation. The possibility of adjusting model parameters in accordance with the obtained results increases the advantages of this approach (Quadri *et al.*, 2019). In addition, the use of LUT tables reduces the volume of calculation operations of linearization, since calculation operations are replaced by operations of searching for previously calculated values of the no-load characteristic (NLC) and the short-circuit characteristic (SCC).

Values of EMF or reactive resistance that do not coincide with the marker points of the LUT table are searched for by linear interpolation during modelling. The application of numerical methods for solving nonlinear equations with the help of LUT gives a practical opportunity to build a nonlinear SG model for an autonomous power plant (Michna *et al.*, 2014).

The nature of the formation of controlling influences on the generation of the EMF value of the SG is influenced by the dependence of the inductance of the excitation winding L_f on the current I_f flowing in the winding. Then, in the presence of numerical values of the function $L_f=f(I_f)$, obtained experimentally, a corresponding 1-D Lookup Table is built in the MATLAB Simulink environment. This table is used in the construction of the SG excitation winding modelling unit, the diagram of which, according to (6), is presented in Figure 7.

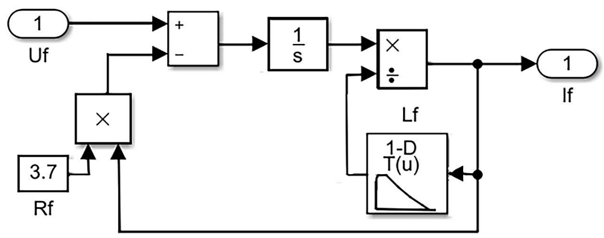

Figure 7. Modelling block of the SG excitation winding

Note: Rf and Lf – active resistance and inductance of the excitation winding; Uf and If – voltage and current of the excitation winding

Source: created by the authors based on O. Zenovych *et al.* (2020)

The data needed to construct the table are obtained using an experimental setup (Kulinchenko *et al.*, 2023a). The experimental values obtained during the generation of voltage by the G-273 generator in the EGU installation form the desired no-load characteristic:

$$E=f(I_f, \omega_e). \tag{14}$$

Function (14) reflects the dependence of the EMF of the generator on the excitation current I_f and the frequency ω_e, which differs from the speed of rotation of the turbine ω_T by the factor p – the number of pole pairs. The presence of function (14) allows us to build a tabular form of 2-D Lookup Table, which, in interaction with other blocks of the modelling diagram, forms a nonlinear model of the SG. The general diagram of the SG model is shown in Figure 8.

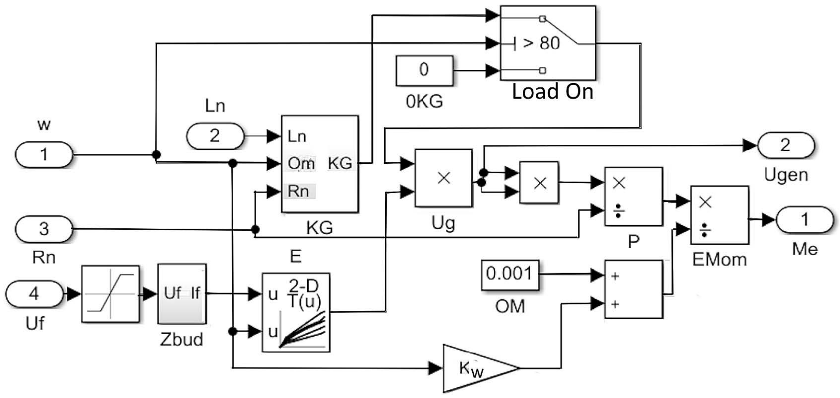

Figure 8. General diagram of the SG model

Note: ω – frequency of the generator magnetic field rotation; Rn and Ln – active resistance and load inductance; Uf – excitation winding voltage; Ugen and Me – voltage and torque moment of the generator

Source: created by the authors

In this scheme, in addition to the equations of the model (6), (13), (14), the function of imposing an electric load after reaching the minimum speed of rotation of the turbine is implemented. To prevent the collision of division by "0", the minimum value of the rotational speed of the turbine shaft is introduced in the diagram, the torque moment of which is not able to overcome the initial torque moment of friction of the SG.

Structural synthesis of the regulator. Returning to the structure of the EGU model, we can state that the output voltage of the SG installation is regulated through two control channels. At the same time, the two output parameters of the EGU model, determined by the modes of its operation, are feedback signals (Fig. 4) for the regulator. In this way, a two-dimensional control system is formed, for the description of which the state space apparatus is used (Baliuta & Kuievda, 2017). In order to practically use the apparatus of the state space during modelling, the plant is linearized at a separately selected operating point of the installation with parametric constraints. However, such an approach is justified only in cases where it is a matter of stable modes of EGU operation. In the current case, with changes in the electrical load, there are abrupt changes in the controlled parameters of the SG, the use of parameters of stable modes for modelling transient modes is not justified.

When considering options for building the structure of multidimensional regulators, attention is drawn to the existence of cross-connections between control channels. Considering the specifics of the studied plant, it can be stated that changes in the excitation field of the SG only indirectly affect the rotational speed of the EGU, while the effect of changes in the rotational speed on the excitation field of the SG can only be estimated theoretically. The study of the interaction of mechanical and electromagnetic processes of power plants involves taking into account the possibility of simultaneous influence of both controllers on changes in output parameters. At the same time, it can be considered that the work of one control channel is a disturbance for another. Then the quality of the control will depend on the ratio between the time constants of the channels, which are determined by the features of the operation of different types of turbines, in particular VT.

Analysis of the results of previous studies by H. Kulinchenko *et al.* (2023b) with VT and parameters of the G-273 generator, which is used in the experimental EGU installation, shows a significant difference in the time constants of the control loops. At the same time, the speed of the control circuit of the excitation of the SG is significantly greater than that of the control circuit of the rotational speed of the installation shaft. This makes it possible to build the structure of the regulator as a set of AER and ARSR subsystems with setting parameters that correspond to the formed criteria of EGU control (Fig. 9).

The diagram includes the Sim Zbur disturbance simulator, which simulates the transient processes of changes in the load of SG. Observing the nature of changes in the controlled parameters of the EGU allows us to adjust the parameters of the involved regulators. The task of ARSR is performed by RReg (relay regulator), and the tasks of control the voltage of the SG are solved with the help of the PID regulator (AER), which controls the value of the excitation current. This representation of the plant control structure greatly simplifies the process of parametric synthesis of the regulator, since it is assumed that these control loops, due to the difference in their time constants, are autonomous. The software-algorithmic connection of these circuits is built in accordance with the tasks of increasing the system's stability margin and obtaining additional effects regarding the quality indicators of the transient processes of the EGU installation.

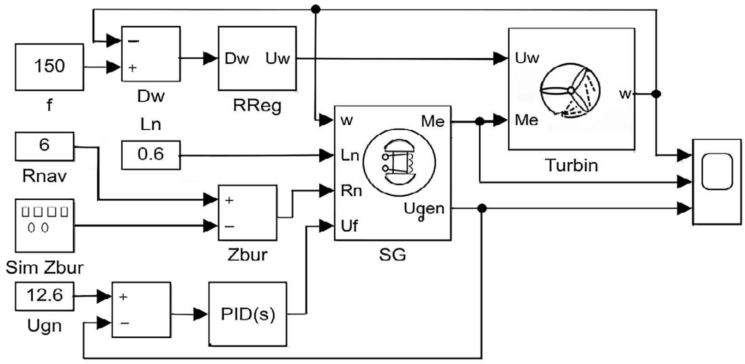

Figure 9. The general control diagram of the EGU

Note: f – generator voltage frequency setpoint; Rnav and Ln – active resistance and load inductance; Ugn – generator voltage setpoint; RReg – rotational frequency relay regulator; SG – synchronous generator; Turbin – turbine

Source: created by the authors

Traditionally, during the construction of regulators of power plants, the main attention is paid to the AER, since it is believed that this circuit directly affects the voltage of the generator. At the same time, considering the limited energy resource of the influence on the excitation field, forcing chains are introduced into the composition of AER or vice versa, when overcoming oscillations and swinging effects – compounding (Rajamand, 2020). To overcome the electromagnetic inertia of the excitation circuit, a control effect is formed, which responds not only to the absolute deviation of the output voltage, but also to the rate of its change. In "strong action" regulators, derivatives of other quantities are used, which determine the modes of operation of the SG, but this is impractical for power plants of small power generation. On the other hand, increasing the complexity of the AER complicates the process of adjusting the regulator parameters from the point of view of ensuring stability. This follows from the dynamics of the interaction of electromagnetic and mechanical processes of EGU.

It can be seen from the equation of the SG model (13) that the change in the frequency of rotation of the EGU, which occurs when the load changes, determines the current reactive resistances of the SG, which also depend on the voltage of the generation U_G. Therefore, the task of stabilizing the rotational frequency of the EGU, which is solved by ARSR, becomes decisive when building the EGU control algorithm, since the stability of the generation frequency also determines the overall quality of object control.

Solving the problems of the parametric synthesis of the regulator is usually based on the results of the estimation of plant parameters. Then the parametric identification of the model involves the determination of its parameters $\prod = (\pi_1, \pi_2, \ldots \pi_N)$ in the process of operation of the plant or special experiments with it (Levinskyi & Levinskyi, 2023). It was previously substantiated that due to the non-linearity of the investigated plant, the processing of experimental data obtained directly at the operating object is considered to be the perfect means of parametric identification of the model.

As it follows from the analysis of the tasks of the regulator and its structure, stabilization of the frequency of rotation of the SG shaft is a mandatory condition for the stable operation of the EGU. Previous studies of the autonomous vortex turbine rotational frequency control circuit (VTC) have shown the effectiveness of using a 3-position relay generator (Fig. 9). Having sufficient speed to control the stepper motor of the gas flow valve, this regulator provides the necessary quality of regulation of VTC (Kulinchenko *et al.*, 2023b). However, the prospect of using such a regulator in the EGU is determined by the results of the VT/SG unit. The developed model (Fig. 9), which considers the experimentally obtained parameters of the SG and the known parameters of the VT, allows to simulate the transient characteristics of the EGU parameters in the MATLAB/Simulink environment. Visualization of these characteristics is shown in Figure 10.

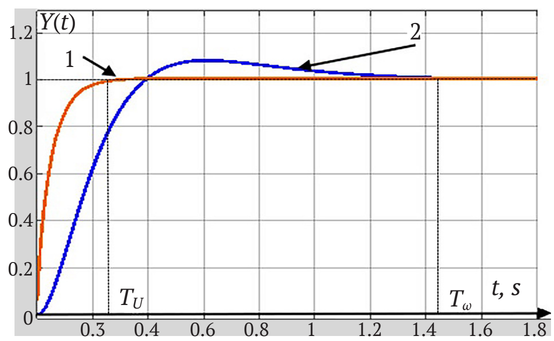

Figure 10. Transient characteristics of EGU parameters

Note: Y – relative units; 1 – transient voltage characteristic; 2 – transient characteristic of rotational frequency; T_U – excitation winding voltage control time; $T\omega$ – rotational frequency control time

Source: created by the authors

From Figure 10, it is possible to estimate the time of transient processes of EGU circuits. The obtained oscillograms confirm the difference in the control time of the EGU control circuits, which is the basis for building the structure of the regulator according to the autonomous structure. The tasks of the parametric synthesis of the EGU regulator stem from the criteria of minimizing the control time and the overregulation value. At the same time, considering the difference in the dynamics of the control channels, there is a need for interaction settings between the circuits, since the control actions of one parameter are disturbances for another. Then, the task of developing control system settings algorithms is added to the tasks of parametric synthesis.

The results of stabilization when turning on the adjusted regulators, obtained on the model of Figure 9, are shown in Figure 11. The demonstrated possibility of setting the parameters of the EGU regulator, which is carried out using the MATLAB tool – *SISOTOOL*, allows us to perform step-by-step sequential coordination of the EGU circuits and proceed to the practical implementation of the regulator.

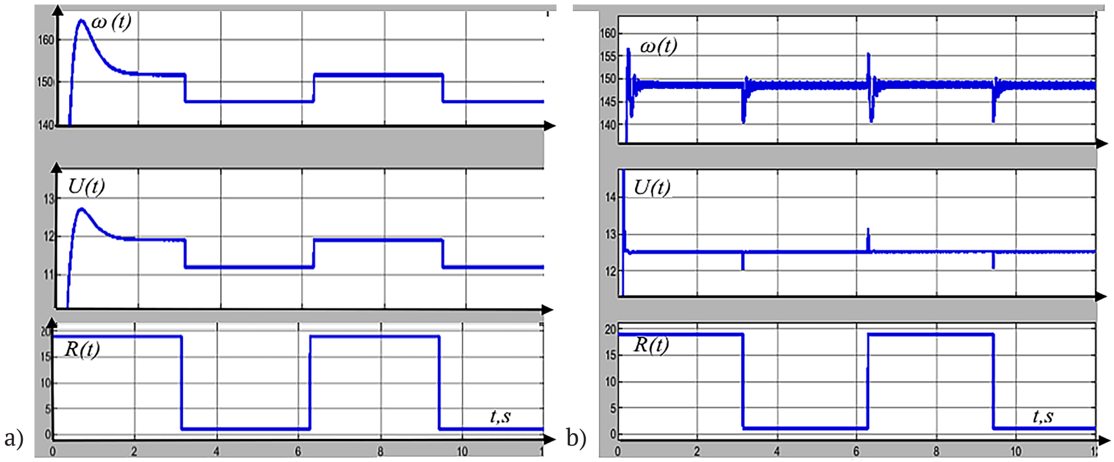

Figure 11. Oscillograms of the EGU output parameterU
Note: a) – oscillograms of generation parameters, regulators are turned off; b) – oscillograms of generation parameters, regulators are turned on; ω(t) – rotational frequency; U(t) – generation voltage; R(t) – load resistance
Source: created by the authors

The effectiveness of the developed regulator can be illustrated by the oscillograms shown in Figure 12. It allows us to stabilize the rotational frequency and voltage of the generator within 5%.

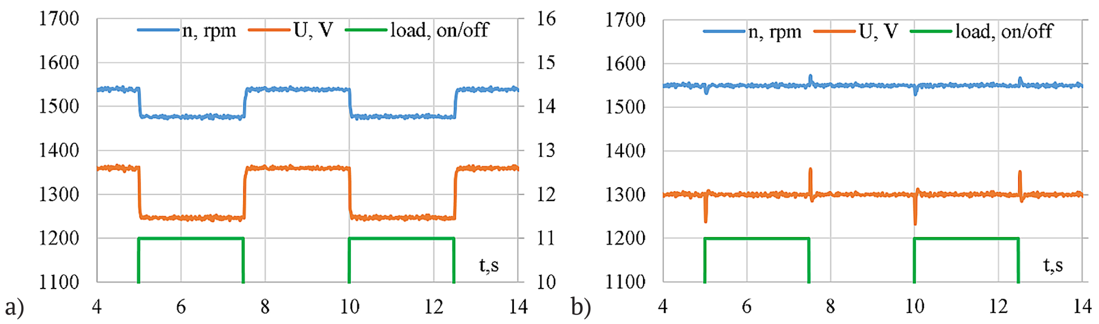

Figure 12. Oscillograms of the EGU experimental installation output parameters
Note: a) – oscillograms of generation parameters, regulators are turned off; b) – oscillograms of generation parameters, regulators are turned on; n – rotational frequency; U – generation voltage; load – load status
Source: created by the authors

Considering the place of EGU in alternative energy, it is advisable to consider the specifics of power plant management, which differ in the source of mechanical energy. Regarding steam turbines, it can be noted that with the development of software and technical control tools, the corresponding classical methods of building control devices are improved to the introduction of digital control platforms. This is due to an effort to make more efficient use of resources spent on operation and maintenance of existing equipment by improving system performance. Factors stimulating the introduction of modern control technologies are the insufficient speed of steam turbine (ST) valve servomotors and the drift of parameters over time. Exploring control systems and ways to improve steam power plant controllers, M. Dulaua & D. Bica (2014), V.N. Severin *et al.* (2016) paid the main attention to the stabilization of the rotation speed of the ST, taking into account a certain inertia and insufficient speed of the controlled equipment due to the large power of the ST. In the sector of hydro-turbine equipment, there is also a prevailing trend towards the introduction of systems for controlling the frequency of rotation of the hydro-turbine rotor. At the same time, the development of control systems is reduced to a plant linearized description. As O. Hasiuk (2023) noted, "improving the dynamic characteristics of speed regulators of hydroturbines requires the development of nonlinear mathematical models followed by the analysis of transient processes in the hydraulic drive of the speed regulator". With a similar purpose, in this study, linearized VT models were used, and SG nonlinearities were taken into account in the development of EGU regulators.

Investigating the construction of control systems of alternative or distributed energy, S. Boiko *et al.* (2021), focused on finding their additional functionality. Accordingly, when developing the structure of power plants, they set the goal of providing consumers with a stable voltage of a constant frequency regardless of changes in system parameters. In this case, the system moves from direct control of the object to a higher level of control – solving optimization problems. In this paper, a similar problem of electricity generation according to the given parameters is also solved in relation to the EGU.

Research by S.M. Vaneev *et al.* (2019) are devoted to increasing the energy efficiency of utilizing turbine generators by optimizing their parameters and characteristics. The perspective of the development of small power utilization turbogenerators is determined by the availability of hardware and software tools that ensure the implementation of turbogenerators in the gas transportation system of Ukraine. The results of this study allow us to move on to the construction of the EGU with the corresponding automated control systems. The successful implementation of alternative energy sources solves the problem of decentralization of energy supply by regulating energy system consumption peaks.

According to S. Denysiuk & I. Boiko (2021), optimization of operating modes of Microgrid with diesel generators can be considered as a decentralization option. Considering the criterion of optimization – the reduction of fuel consumption of diesel generators, the task of direct influence on the amount of generated electricity by technical means of automation has not been solved at the present time. Analysing the development trends of power plant control systems, it can be stated that load frequency control (LFC) has moved from traditional optimization methods to hybrid metaheuristic optimization. This is due to the fact that the introduction of hybrid power systems with solar, wind and diesel power plants leads to a decrease in the overall inertia of the power system. Thermal power plants operating on coal, and which are basic in the energy system, compared to renewable energy sources, have greater inertia. When energy flows during times of load in the power system, frequency fluctuations are observed, which are associated with different inertia of the system blocks. Research by I.A. Khan *et al.* (2023) show that compensation of fluctuations at the current stage of development of power system control systems is carried out with the help of virtual inertial devices, which are implemented on the basis of hybrid and cascade controllers. At the same time, such a phenomenon is not observed during the operation of autonomous power plants. Therefore, an alternative to complex virtual inertial devices is the approach, according to which the control of the installation is based on the coordination of the plant coordinate settings, which is considered in the work of A.A. Gursky *et al.* (2020). In the EGU aspect, these coordinates are the output voltage and the generation frequency. The approach proposed in this paper to solving the tasks of the coordinated functioning of the AER and the ARSR allows to improve the damping characteristics of the system.

Therefore, the development of the EGU model made it possible to determine the rotation parameters of the VT and the generator, which affect the quality of electricity generation. To ensure reliable and effective regulation of the frequency and voltage of the generator, a structural diagram of the EGU model has been developed, which takes into account the interaction of the turbine torque moment, the generator reaction torque moment, and the electrical load. The nonlinear SG model is developed using a family of transfer functions and numerical modelling methods in the MATLAB Simulink environment, which allows considering the specifics of the turbine unit operation and improves the accuracy and stability of regulation.

CONCLUSIONS

A model of the synchronous generator used in the experimental installation of the physical model of the expander-generator unit was developed. The use of the Lookup Table option of the MATLAB environment in the model made it possible to consider the nonlinear characteristics of the control object obtained from datasheet data and experimentally. Using the synchronous generator model and the previously developed turbine model, a EGU model was developed, which is part of the autonomous electricity consumption network. Its use allows us to study control processes and assess possible errors associated with simplifying the description of the control object in the process of building regulators. The evaluation of the dynamic characteristics of the control channels of the studied two-dimensional control object made it possible to virtually untie the channel regulators and consider them autonomous. This made it possible to coordinate the settings of the automatic regulators of excitation and rotor speed of the EGU generator, to investigate the operation of the regulators on the EGU model and to proceed to their practical implementation.

The test of the previously developed microprocessor rotational speed regulator of the vortex turbine and the excitation regulator of the synchronous generator, which are implemented on the basis of the Siemens Simatic PLC S7-300 CPU 314C-2DP, confirmed the feasibility of the approach to the settings of the EGU regulators proposed in the work. Developed EGU regulators provide stabilization of the output parameters of the unit under conditions of electrical load disturbances. The design features of the experimental setup, due to the slight inertia of the processes accompanying the generation process, did not provoke the occurrence of frequency fluctuations of the generated voltage. At the same time, changes in the frequency of rotation of the EGU shaft, which accompany changes in the electrical load, have a fading character.

The perspective of further studies of EGU regulators is presented as the implementation of proven methods of their development in the design of the gas distribution network system. Another direction of using this research is the approbation of various control laws when simulating disturbances at power plants of alternative (renewable) energy. The closest prospect of research is seen in the development of EGU regulators using jet turbines and turbines with a higher generation capacity.

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CONFLICT OF INTEREST

None.

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Дослідження регулятора детандер-генераторного агрегату

Анотація. Актуальність дослідження визначається завданнями підвищення ефективності енергоустановок альтернативної та відновлюваної енергетики. Мета роботи полягає в розробці методики координації налаштувань автоматичних регуляторів збудження і швидкості обертання ротора генератора з вихрової установки детандер-генераторного агрегату, що входить до складу автономної мережі електроспоживання. Для досягнення поставленої мети використовувалися методи математичного моделювання у середовищі MATLAB, фізичного моделювання, обробки експериментальних даних, теорії автоматичного керування, теорії магнітного поля, теорії електричних машин, програмування мікропроцесорних пристроїв. Зважаючи на необхідність розширення бази альтернативних енергоджерел, розглядалася задача керування енергетичною установкою утилізації надлишкового тиску газотранспортних мереж. Дослідження регулятора детандер-генераторного агрегату ґрунтувалося на моделі, що відображає взаємодію процесів механічної та електричної природи. Опису цих процесів відповідала сукупність нелінійних диференційних рівнянь. Точне врахування нелінійностей об'єкта керування, що розглядався, ускладнює реалізацію відповідної мікропроцесорної систем керування. Моделювання спрямоване на досягнення компромісу між необхідною точністю регулювання об'єктом та можливостями спрощення структури керування об'єктом. Використання експериментальних і паспортних даних пристроїв дозволило оцінити динаміку обертання турбіни та генерації напруги, формуючи чинники розв'язки контурів керування. Застосування MATLAB з опцією Lookup Table дозволило здійснити багатоточкову лінеаризацію нелінійного опису процесу, прискоривши моделювання і налаштування регулятора. Це важливо для координації налаштувань контурів керування частотою обертання та вихідною напругою, зважаючи на протиріччя між швидкодією регулятора та мінімізацією коливань частоти генерації. За отриманими результатами розроблено регулятор детандер-генераторного агрегату, який забезпечує стабілізацію вихідних параметрів агрегату в умовах дії збурень електричного навантаження. На практиці отримані дані можна використати в інтеграції відновлюваних джерел енергії до загальної енергосистеми через оптимізацію роботи генераторів

Ключові слова: вихрова турбіна; частота обертання; координація налаштувань; нелінійна модель; синхронний генератор; регулятор збудження