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Autonomous power supply system for consumers

Abstract. The study aimed to develop the structure of an imitation model of an autonomous power supply system for consumers, which includes subsystems of wind turbine and alternator models, and to describe the characteristics of its components. The procedure for functioning the elements of the autonomous power supply system for consumers and the peculiarities of their interaction were considered. The imitation model of the autonomous power supply system for consumers was created in the Simulink (Matlab) software environment using standard and specialised blocks of the Simulink library, which will allow the most visual and detailed display of the mechanisms of interaction of objects in the automated power supply system for consumers and analysis of the results obtained. A simulation model of an autonomous consumer power supply system, wind turbine, and alternator subsystems has been developed. The resulting simulation model and its main components were described in detail. To ensure maximum efficiency of converting wind energy into electricity, a model of a universal step-up and step-down voltage converter AC-DC_MPPT_Wind with the function of maintaining the

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maximum power point, which served as a wind turbine load and a charger, and whose output is connected to a battery, was created. The features of the DC-AC_inverter subsystem model were the ability to adjust the output voltage and current frequency and select the output current modelling mode – AC or DC, depending on the nature of the research tasks. An experiment conducted using this model was also described and analysed. The results showed that the simulation model of the autonomous power supply system for consumers worked correctly and performed all the specified functions. The results can be used in industrial enterprises to ensure energy independence and reduce electricity costs

Keywords: simulation model; energy independence; wind energy sources; electricity; wind turbine

INTRODUCTION

Wind energy's potential by 2030 depends to a large extent on climate and energy policies determined at the EU level. The potential for wind power development until 2030 largely depends on climate and energy policies defined at the EU level. In particular, the governance of the Energy Union, the Renewable Energy Directive for the period after 2020, the Emissions Trading System (ETS), and the European Electricity Market Framework will have a significant impact not only on the pace of wind energy development but also on other renewable energy sources at the national level. (Wind Europe, wind energy in Europe, scenarios for 2030, 2017). The technologies used in renewable energy and improving energy systems must compete with climate change and consider greenhouse gas emission reduction targets, according to A. Tantau *et al.* (2021), the spread of renewable energy sources (e.g., wind or photovoltaic installations) must be balanced by new technologies and tools for new energy systems characterised by intermittent and uncertain energy generated and new measures to ensure the stability and reliability of the energy system. Y. Charabi *et al.* (2019) noted that from solar panels to wind turbine generators, a wide range of devices can convert ambient energy into a more useful form, like electricity.

Iu. Zachepa *et al.* (2022) presented a mathematical model of the operation of a local autonomous power supply using a diesel generator as the main power source. The primary source of mechanical energy was a diesel internal combustion engine equipped with an automatic speed regulator. The engine was based on the classical principle developed by Polzunov and Watt. Continuous power generation through wind power was mainly the most crucial way to use wind energy. G. Zining (2021) claimed that this power generation method has been highly valued by various countries, mainly using a natural energy source for power generation. This technology had many advantages in the actual application process and had a relatively important role in energy-saving renewable energy and crucial ecological protection.

Transport infrastructure facilities are located in an open area, providing sufficient space for placement and simplifying the orientation of photovoltaic solar panels in the sun (Kozyrsky *et al.*, 2020). The research presented by A. Skrypnyk *et al.* (2023) indicated the prospects for developing solar power sources in Ukraine. The authors presented an optimisation model of electricity generation that corresponded to the state of the energy market in 2019, which made it possible to assess the contribution of reverse externalities of each electricity sector and estimate external tariffs for each electricity generation sector.

The development and benefits of renewable energy technologies mean that their applications are constantly expanding. The development of roads, transport systems, and electric mobility also increases the demand for electricity. According to D. Kurz *et al.* (2024), roads occupy a specific area that can be used for the installation of wind turbines or photovoltaic systems, which can be used to power, among other things, electric vehicle charging stations and road technical infrastructure (road maintenance areas, tunnel lighting, road signs).

The introduction of autonomous energy supply systems for consumers is driven by the need to improve the reliability of electricity supply, reduce electricity losses, and modernise power grids. A centralised power supply system with significant technological losses and a vast distribution network can compromise the quality and reliability of power supply to remote locations. Using autonomous systems based on renewable energy sources can solve this problem. However, the practicality of using a particular energy source requires the development of simulation models of these systems to optimise the determination of their design parameters. To solve this problem, this study develops a simulation model of an autonomous energy supply system for consumers, subsystems of wind turbines, and alternator models.

MATERIALS AND METHODS

The study was conducted at the National University of Life and Environmental Sciences of Ukraine and Ternopil Volodymyr Hnatiuk National Pedagogical University in 2023-2024. An imitation model of an autonomous power supply system for a consumer and subsystems of wind turbine and alternator models was developed as part of the study. The simulation model was developed using Simulink software (Matlab) and standard and specialised blocks of the Simulink Library – Simscape, SimElectronics, and SimPowerSystem sections.

The structure of the simulation model of an autonomous power supply system for consumers based on the use of a renewable wind energy source to generate electricity using a transmissionless wind turbine with a vertical rotor is shown in Figure 1.

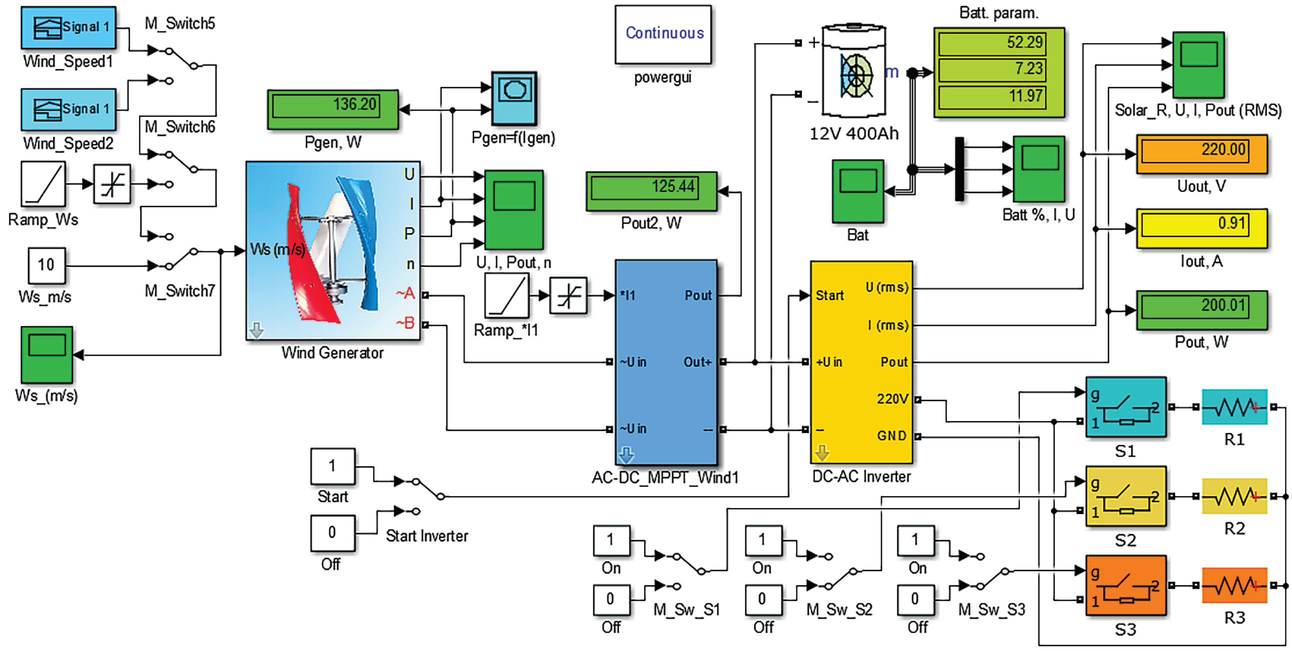


Figure 1. Structure of the simulation model
Source: compiled by the authors of this study

The structure of the model (according to Fig. 1) included the following main elements:

- wind turbine;
- universal step-up DC-DC_MPPT_Wind1 DC-DC_MPPT_Wind1 DC-DC_MPPT_Wind1 universal step-down converter with the function of maintaining the maximum power point (Maximum Power Point Tracking – MPPT), which was the load of the wind turbine and was intended to charge the battery;
- a battery with a nominal voltage of 12V and a capacity of 400 Ah was selected from the Simulink Library of blocks.

The subsystems of the DC-DC_MPPT_Wind1 converter and the DC-AC_inverter were designed as simplified "behavioral" models that reproduce the basics of converter operation without the need to simulate individual switching events associated with pulse width modulation (PWM) processes. They were based on energy conservation and conversion laws, considering input and output power balances and energy losses during conversion. The simplified simulation model structure facilitated a more concise mathematical description, reducing the computational operations required per unit of time. This optimisation led to significant reductions in both simulation time and computer resource utilisation. As a result, the simulation of 24 hours of system operation was completed within a few minutes, an essential factor in the study of long-term processes, the entire cycle of which can be measured in hours or even days.

The wind generator (WG) was represented by the block of the Wind_Generator subsystem, which also included the Wind_Turbine and Generator subsystems (Fig. 2).

The presented wind turbine model contained the basic mathematical and logical operations used to model a wind turbine's performance (Fig. 3).

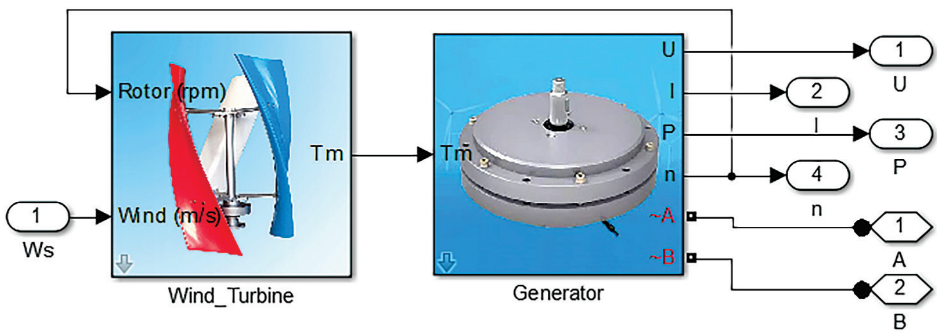


Figure 2. Structure of the Wind_Generator subsystem
Note: Ws – wind speed, m/s; Tm – transmission; U – voltage, V; I – current, A; P – power, W; n – rotor speed; A, B – alternating voltage, V
Source: compiled by the authors of this study

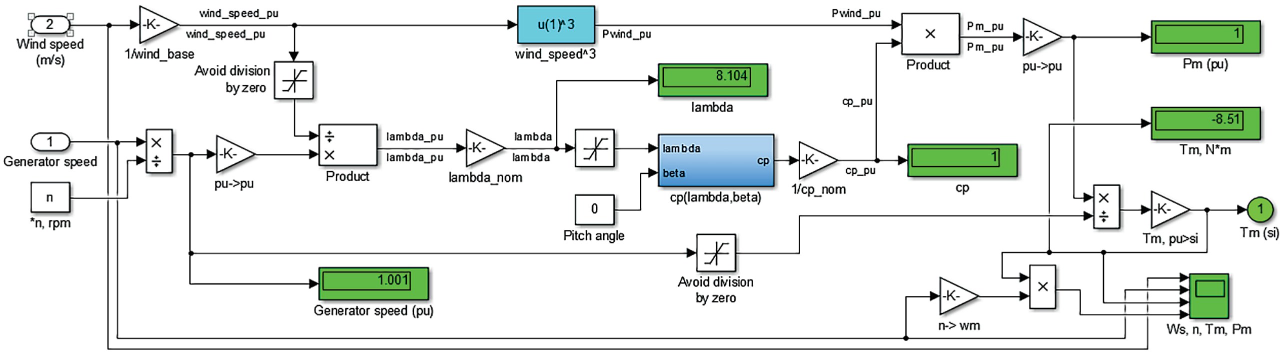


Figure 3. Structure of subsystems of wind turbine models

Source: compiled by the authors of this study

The main elements of the wind turbine model were:

1. Input parameters: wind speed (wind speed, m/s) – a parameter that determines the wind speed in meters per second; generator speed (generator speed, rpm) – a parameter that determines the generator speed in revolutions per minute (rpm).

2. Input value converters. Wind and generator speed input values were converted to conventional units for further calculations.

3. Blocks for calculating model parameters: Lambda (λ) was the ratio of the wind turbine blade tip speed to the wind speed; Cp (power factor) was a function of λ, and the blade angle (beta); Pm (mechanical power, pu) was calculated based on Cp and wind power.

4. Unit for converting mechanical power to torque (Torque, Tm).

5. The model outputs include wind speed, generator speed, torque, and power, which could be shown in conventional units (pu) or system units (SI).

The model of an alternator made it possible to illustrate the detailed structure and functioning of an electric generator's control and monitoring system. It presented how various parameters were calculated and monitored in real-time to ensure efficient generator operation (Fig. 4).

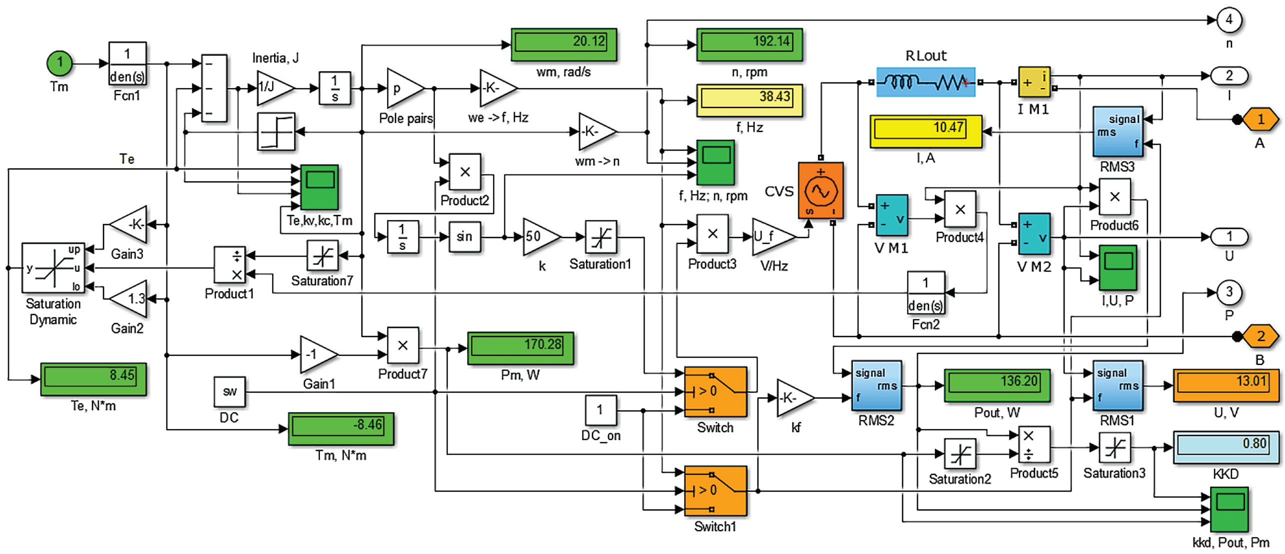


Figure 4. Structure of alternator subsystems

Source: compiled by the authors of this study

The main components of the alternator model were Inertia – a block that takes into account the moment of inertia of the rotor; Pole pairs – blocks for calculating the number of generator poles; Frequency conversion – blocks for converting the rotational speed to different units (radians per second, revolutions per minute, hertz); Saturation – blocks that limited the output values to prevent excessive amplification; Gain – blocks for increasing or decreasing the signal amplitude; Root et al. (RMS) – blocks for calculating the root mean square value of an alternating current; Switches – blocks for switching between different input signals; Multiplication blocks – blocks for multiplying signals and calculating power; Various output parameter blocks: Output torque, Nm; Angular velocity, rad/s; Rotational speed, rpm; AC frequency, Hz; Current, A; Voltage, V; Power, W.

The simulation model of the generator (Fig. 4) was based on the use of a controlled ideal voltage source (CVS) with a series-connected active-inductive element RLout, which is equivalent to the internal resistance and inductance of the stator winding, which, in particular, allowed us to determine the electrical losses in the stator (and the associated efficiency) and its reactive power component. It also included VM1, VM2, IM1, RMS1 – RMS3 voltage and current meters with corresponding digital indicators and oscilloscopes. The input value of the source controlled by CVS can be either DC or AC emf (depending on the selected modelling mode in the subsystem settings window). In the case of the selected "AC" modelling mode, the input of the CVS source was supplied with the EMF value, the amplitude Em and frequency f of which were determined by the mechanical characteristics of the rotor rotational motion ωm, its induction (magnetic flux value) Fm, and the number of pairs of stator poles p.

RESULTS AND DISCUSSION

The input value for the developed wind turbine was the wind speed (m/s), which could be set in several ways: as a constant – Ws_m/s, monotonically increasing or decreasing – Ramp_Ws, or arbitrarily changed according to statistical data during a specified period (day) using Wind_Speed1, Wind_Speed2 (Fig. 5a). The signal source was selected by changing the states of the M_Switch5 – M_Switch7 switches. The oscilloscope Ws_(m/s) allowed us to display the set wind speed parameters graphically. The output parameters of the wind turbine (voltage, current and its frequency, power, rotor speed, and torque) were determined from the overall balance of mechanical and electrical power, taking into account mechanical losses associated with static and dynamic rotor friction, its moment of inertia, and electrical losses in the stator winding. Most of them were reproduced by the oscilloscope U, I, Pout, n, and the digital display Pgen, W. The dialogue window for setting the generator parameters is shown in Figure 5b.

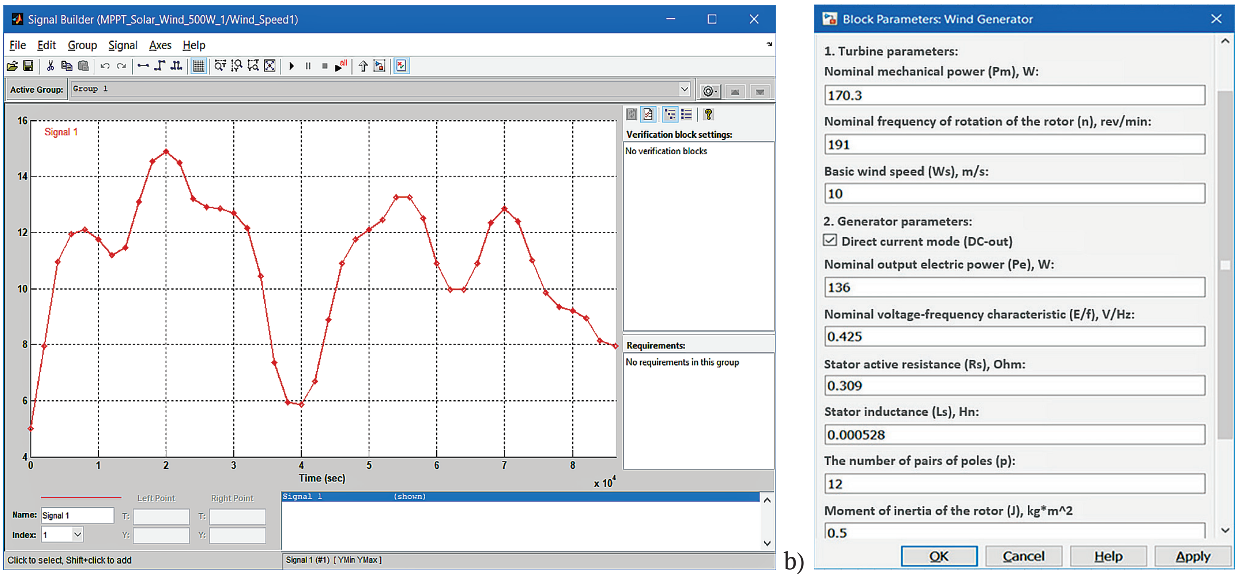
a)  b)

Figure 5. Analysis of wind speed and turbine settings
Note: a – formation of a daily wind speed graph, b – wind turbine parameter settings window
Source: compiled by the authors of this stud

The mechanical component of the rotational motion of the rotor ω_m (angular velocity, rad/s) was defined as the integral of dividing the difference of the components: torque T_m, electromagnetic torque T_e, static moments T_{kc}, and dynamic (viscous) friction T_{kv} by the moment of rotor inertia J:

$$\omega_m = \int \frac{T_m - T_e - (T_{kc} + T_{kv})}{J} dt \cdot \quad (1)$$

The electric frequency of the generator is defined as the product of the rotor angular velocity and the number of stator pole pairs divided by 2π:

$$f = two \frac{p\omega_m}{2\pi}; \quad (2)$$

$$E_r = 24 * 20 * \frac{0.00022}{0.0065} = 16.246\,(V). \quad (3)$$

The coefficient k_{ef} of the voltage-frequency characteristic, based on the known nominal values of the electromotive force E and the period $T = 1/f$, is:

$$k_{ef} = \frac{E}{f} = E * T = 16.246 * 0.026 = 0.4224 \text{ V/Hz}. \quad (4)$$

During the generator's operation simulation, by integrating the product $p\omega_m$ and calculating the sine from the result, harmonic oscillations were obtained with the corresponding frequency related to ω_m by the above dependence and amplitude values from -1 to +1. Since the amplitude value of the generator's emf is directly proportional to the rate of change of the magnetic field induction (electric frequency). The shape of the output voltage curve is theoretically close to rectangular (due to the design features of the stator and rotor magnetic poles). To reproduce these parameters in the model, it was necessary to increase the amplitude of the obtained sinusoidal oscillations by 50-100 times (using a multiplier) and limit it to the same unit value with the limit function. In this way, a signal whose shape was close to rectangular was generated with an amplitude that did not depend on frequency. To obtain a monotonically increasing dependence of the output EMF on the rotor speed (electric frequency), it was necessary to first determine the amplitude value of the EMF at the rated frequency, as well as the associated coefficient k_{ef} f of the voltage-frequency response (*E/f*). It was obtained a monotonically increasing generator EMF with frequency by multiplying this coefficient by the signal frequency at the current time and the nominal EMF amplitude.

Based on the calculated data of the physical model of the generator (for the rated rotor speed), namely the resultant rotor magnetic flux $F_m = 0.00022$ Vb, the time interval of magnetic flux change $dt = 0.0065$ s (equal to $\pi/2$, the entire period $T = 0.026$ s, respectively), the total number of coils on both sides of the disc rotor – 24, the number of turns of one coil winding – 20, according to the formula $E_m = -dF_m/dt$ (for one turn), obtained the total amplitude value of the generator's EMF.

DC out mode, the CVS source receives the calculated EMF value, which is proportional to the rotor speed by the k_{ef} coefficient and equivalent to its actual AC value. This mode significantly reduced the model execution time, essential for modelling long-term processes with a daily or seasonal cyclic nature. At the same time, the main electromechanical characteristics of the generator and the overall power balance during the conversion of mechanical energy into electrical energy were preserved.

The electromagnetic torque of the generator T_e was determined from its total electrical power, taking into account losses in the windings, equal to the product of the output EMF and the load current divided by the current rotor angular velocity ω_m.

The parameters of the wind turbine determined the input mechanical power of the generator and were equal to the product of the nominal rotor speed (rad/s) and torque (N·m); its nominal value, according to the calculations, is 170.28 W. Considering the efficiency of 80%, the generator's electric power is 136.2 W.

Based on the results of modelling the operation of a transmissionless wind turbine generator with a vertical rotor, it was obtained oscillograms of the output voltage and current when it reaches the rated operating mode (Fig. 6a) and graphical dependences of power on load current for different wind speeds (Fig. 6b). As can be seen from the graphical materials presented, the generator's output power is cubically dependent on the wind speed. For its efficient operation, it is necessary to apply an appropriate algorithm with the MPPT function based on the obtained modelling results.

To ensure maximum efficiency in converting wind energy into electricity, a model of a universal step-up/step-down voltage converter AC-DC_MPPT_Wind with the function of maintaining the maximum power point was developed, which serves as a BEV load and a charger, whose output was connected to the battery. The structure of this subsystem is shown in Figure 7.

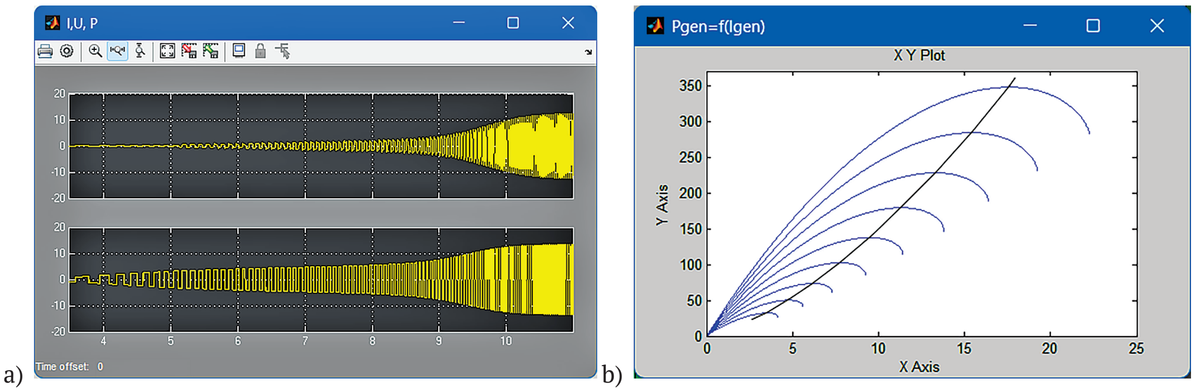


Figure 6. Results of wind turbine modelling

Note: a – current and voltage oscillograms at its output; b – dependence of wind turbine output power on load current for wind speeds of 6-14 m/s

Source: compiled by the authors of this study

The elements of the input load of the AC-DC_MPPT_Wind subsystem were a two-half-period diode voltage rectifier VD1 – VD4, a capacitive filter C1 to reduce input voltage fluctuations, voltage and current meters VM1, IM1, and a controlled current source CCS with a limiting resistance *Ro*. The converter current consumption (input) was determined based on the results of calculations from its output power P'_2 (secondary circuit with losses) by dividing it by the converter input voltage:

$$I(ccs) = P'_2/U_1. \quad (5)$$

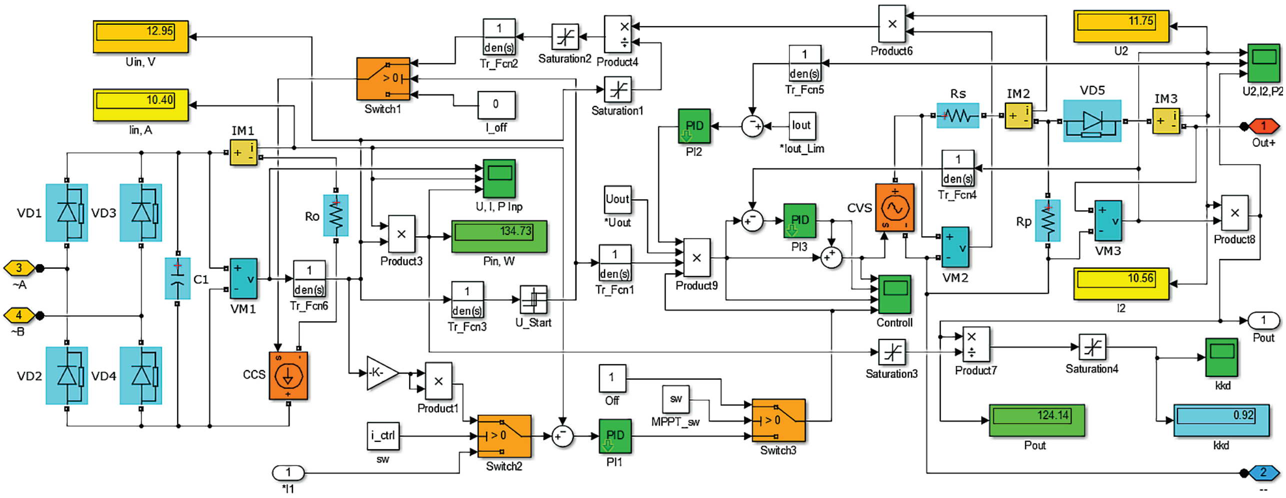


Figure 7. Structure of the AC-DC_MPPT_Wind voltage converter subsystem

Source: compiled by the authors of this study

The calculated current value was set via the external port of the CCS element. The valuable power of the consumer P_2 was defined as the product of the output voltage U_2 (< = 14B) and the load current, which is the battery's charging current. The resistances of the resistive elements set losses in the loaded and idle modes of the converter: series – *Rs*, parallel – *Rp*, as well as the parameters of the diode VD5. I_off sets the power consumption to standby mode.

The MRRT function in the model was implemented as follows: since the power of a wind turbine cubically depends on the wind speed, and its output voltage (EMF) is directly proportional to this speed, the maximum power is achieved when a certain load current is provided at its output, which depends on the square of the wind speed, respectively (for the selected rated mode of the generator at a wind speed of 10 m/s, the value of I_{gen} = 10.4 A according to the modelling results, Figure 6b). Based on this, the task of the MPPT algorithm was to determine and maintain the generator current depending on the wind speed $I_{gen} = f(Ws)^2$ by adjusting the battery charging current. This was achieved by introducing feedback to control the converter's input current, which was compared with the calculated (setpoint) current value calculated from the generator voltage for different wind speeds. The comparison result, with its sign, was fed into the proportional-integral controller (PI1, Fig. 7), whose control signal regulates the converter's output voltage and, associated with affects the battery's charging current and stabilises the input current at the desired level. Under this condition, the generator's output current is directly proportional to the square of its output voltage.

The converter started to operate at a sufficient wind speed when the generator output voltage exceeded the set value (U_{start} > 3 V), according to the MPPT algorithm. The process of charging the battery with a current determined by the wind speed occurred. If it increased to more than 15 m/s, the charging current was limited to the level set in the settings (Fig. 8a) for the selected battery (40 A), and the MRRT function switched to the constant current charging mode. The charging process was completed in the constant voltage mode (14 V), and the current was reduced to the minimum value (0.1 A) (Fig. 8b).

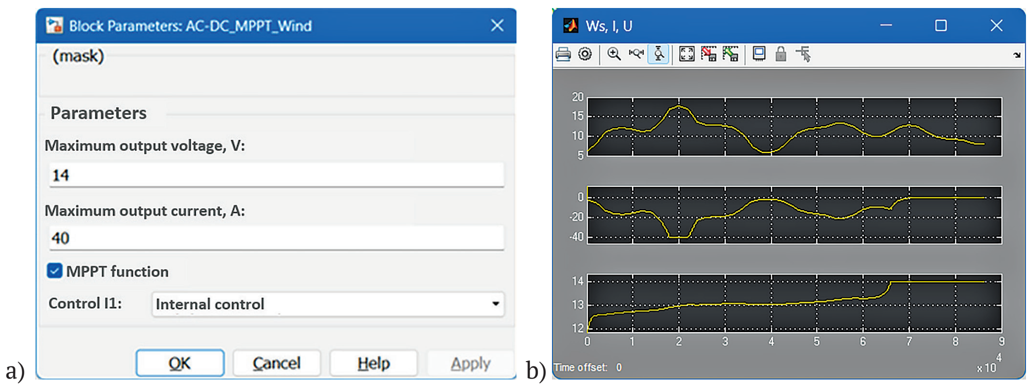


Figure 8. Settings window

Note: a – AC-DC_MPPT_Wind unit; b – time diagrams of wind speed, charging current, and battery voltage

Source: compiled by the authors of this study

The structure of the input load of the DC-AC_inverter subsystem (Fig. 9) is similar to AC-DC_MPPT_Wind, except for the absence of a diode rectifier. It included a capacitive filter C1, voltage and current meters VM1, IM1, and a controlled current source CCS with a limiting resistance Ro. The converter's input current was calculated as in the AC-DC_MPPT_Wind subsystem, from its output power P'2 (including losses) by dividing it by the converter's input voltage. The valuable power of the consumer P_2 was defined as the product of the practical value of the output voltage U_2 (220B) and the inverter load current. The values of the resistances set losses in the loaded and no-load modes of the inverter: series – *Rs*, parallel – *Rp*. I_off sets the power consumption to standby mode.

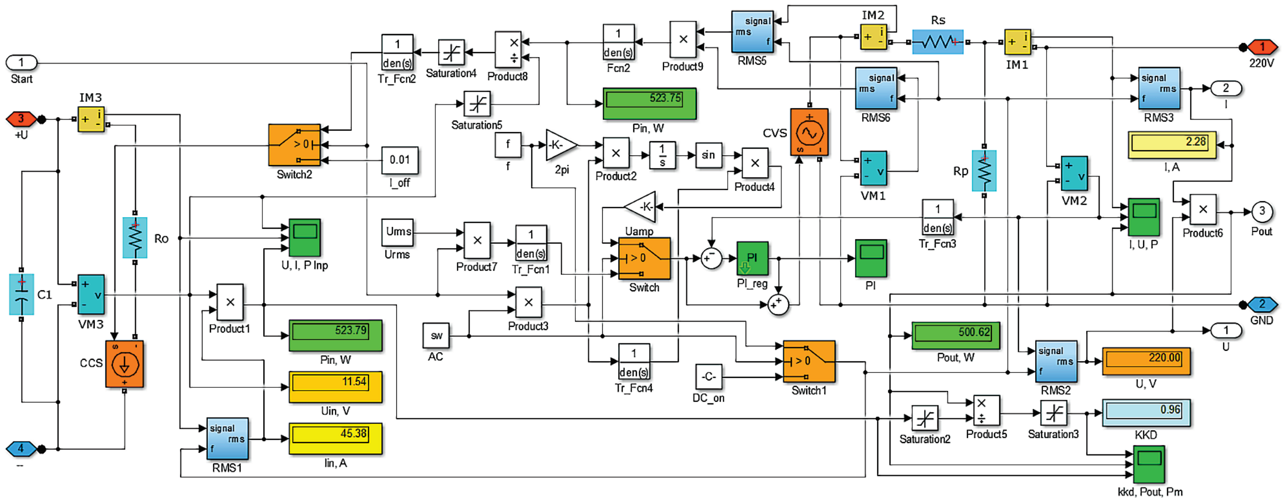


Figure 9. Structure of the DC-AC_inverter voltage converter simulation model
Source: compiled by the authors of this study

The peculiarities of the DC-AC_inverter subsystem model include the ability to set the output voltage and current frequency and select the output current modelling mode - AC or DC, depending on the nature of the research tasks. These modes could be set by selecting the appropriate item from the drop-down menu in the subsystem settings dialogue box (Fig. 10).

The results of modelling the inverter output parameters (current, voltage, power) with the transition from AC to DC are shown in Figure 11.

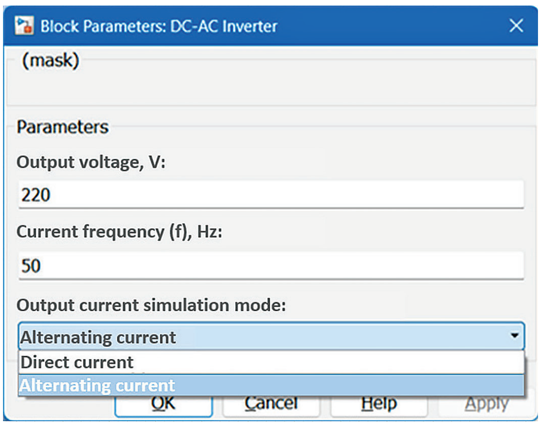


Figure 10. DC-AC_inverter subsystem settings window
Source: compiled by the authors of this study

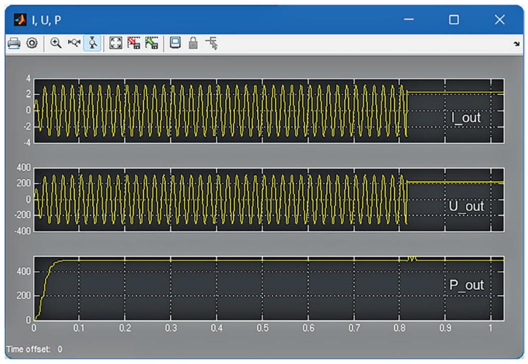


Figure 11. Results of modelling the inverter operation (output parameters)
Note: I_out – current, A; U_out – voltage, V; P_out – power, W
Source: compiled by the authors of this study

The choice of DC mode significantly reduced the model execution time while maintaining the overall balance of the inverter's input and output power, considering losses. It is rationally used in the case of modelling long-term processes.

The study focused on developing a simulation model of an autonomous consumer energy supply system, a subsystem of wind turbine, and alternating current generator models. The model mainly focused on autonomous energy sources, particularly wind energy, as their use is projected to increase. This was also studied in the works of W. Hallgren *et al.* (2014) and F. Porté-Agel *et al.* (2020). The researchers contended that wind energy and other renewable energy sources were projected to experience substantial growth in the upcoming decades, making them indispensable for mitigating climate change and fostering energy sustainability. It is worth noting that according to forecasts, by 2026, solar energy production may increase from 1991 GW to 2708 GW (SolarPower Europe, 2022). J.K. Kaldellis (2002) and O. Apata & D.T.O. Oyedokun (2017) noted that using autonomous power systems was one of the most successful ways to meet the electrification needs of numerous isolated consumers worldwide.

To assess the sustainability and practicality of wind farms compared to other energy sources, it is essential to evaluate their energy use and environmental impact. According to C.K. Gao *et al.* (2019), life cycle analysis has shown that wind farms have a lower carbon footprint than bioenergy plants, making them a more environmentally friendly option.

In addition, the efficient design of wind turbines plays a crucial role in reducing the cost of energy production. M.K. McWilliam *et al.* (2012) identified generator structures optimised for energy production costs by considering population density, wind availability, and proximity to power lines. This method ensures efficient use of wind resources in different regions.

Wind energy, a rapidly expanding green technology, provides a clean, safe, and renewable source of electricity generation. The study by F.H. Khan *et al.* (2021) delved into the available methodologies for sustainably harnessing wind energy, scrutinising recent technological advancements and the prospects of the global wind power industry. One promising avenue for wind energy harvesting involves utilising vehicle-induced turbulent airflow generated by highway traffic to power infrastructure such as highway lighting and telecommunication signalling systems. A.A. Al-Aqel *et al.* (2016) focused on assessing the potentiality of implementing small-scale wind turbines along the highways. Devashish & T. Amarnath (2017) mainly studied different technical aspects of harnessing wind energy.

MATLAB/Simulink was used to model a simulation model of an autonomous power supply system for consumers, including wind turbine and alternator subsystems. In the MATLAB/Simulink environment, block libraries (block sets) represent a modern object-oriented, event-driven, user-friendly approach to problem-solving. Researchers R. Andrienko & K. Klen (2022) presented the simulation modelling results of an autonomous power supply system based on solar panels using accurate data in MATLAB Simulink under constant changes in insolation and load. S. Nasri *et al.* (2017), to prove the reliability and effectiveness of the applied control strategy and its impact on the system's operation, simulated the proposed system using Matlab/Simulink.

The model consists of several vital subsystems, such as a wind generator (Wind_Generator), a wind turbine (Wind_Turbine), and an alternating current generator (Generator). These subsystems interact with each other to ensure the efficient transfer of energy from the wind stream to the electrical grid. A controlled ideal voltage source with active and inductive elements allows for accurate generator modelling. This includes working with both constant and variable values of electromotive force (EMF), which enables the generator's performance to be evaluated in different modes. The main output parameters of the model are rotor speed, torque, voltage, and current. These parameters are displayed on the model's oscilloscope and digital displays. Their display allows for accurate real-time system analysis, facilitating control and monitoring. This enables precise real-time system analysis, facilitating advanced control and monitoring. Detailed calculations were performed to determine the amplitude values of the electromotive force (EMF) and the voltage-frequency response coefficient of the generator. Based on the calculated data of the physical model of the generator (for the nominal rotor speed), the total amplitude value of the generator's EMF $Eg = 16.246$ V. At the same time, the coefficient kef of the voltage-frequency characteristic is $k_{ef} = 0.4224$ V/Hz. During the simulation of the generator's operation in the 'direct current' mode (DC out), the input of the CVS source receives the calculated EMF value, which is proportional to the rotor speed by the coefficient kef and equivalent to its current AC value.

The function of maintaining the maximum power point (MPP) in the model is implemented as follows: since the power of the wind generator is cubically dependent on the wind speed, and its output voltage (EMF) is directly proportional to this speed, the maximum power is achieved if the load current at its output is a specific value, which depends on the square of the wind speed, respectively (for the selected nominal mode of the generator at a wind speed of 10 m/s, the value of $I_{gen} = 10.4$ A according to the modelling results. Based on this, the task of the MPPT algorithm is to determine and maintain the generator current depending on the wind speed $I_{gen} = f(Ws)^2$ by adjusting the battery charging current. This is achieved by introducing feedback to control the value of the converter input current, which is compared with the calculated (setpoint) current value calculated from the actual generator voltage for different wind speeds.

The results generally confirm the significant potential of using autonomous energy supply systems, particularly systems based on wind energy sources. The developed simulation model in MATLAB/Simulink demonstrates efficiency in modelling the operation of such systems, particularly their critical subsystems: wind turbine, wind generator, and alternator.

CONCLUSIONS

The research developed a simulation model of an autonomous power supply system using renewable wind energy. The model was built in Simulink (Matlab) using Simscape, SimElectronics, and SimPowerSystem libraries, which enabled realistic and accurate simulation. The model consisted of key subsystems, including a wind generator, wind turbine, and an AC generator, which worked together to transfer energy from wind to the electrical grid efficiently. A controlled ideal voltage source modelled the generator with active and inductive elements, accommodating constant and variable electromotive force (EMF) values.

Outputs such as rotor speed, torque, voltage, and current were displayed in real time, providing precise system monitoring.

Detailed calculations determined the generator's EMF amplitude (Eg = 16.246 V) and the voltage-frequency response coefficient (k_{ef} = 0.4224 V/Hz) for nominal rotor speed. In DC mode, the input EMF was proportional to rotor speed, ensuring accurate simulation of generator behaviour. The maximum power point (MPP) was maintained through a feedback-controlled MPPT algorithm. Since wind generator power depended cubically on wind speed and EMF was directly proportional to speed, the optimal generator current varied with the square of wind speed. For a nominal wind speed of 10 m/s, the optimal current was I_{gen} = 10.4 A. The MPPT algorithm adjusted the battery charging current via converter input current control, ensuring stable operation under varying conditions.

Simulation confirmed the cubic dependence of output power on wind speed, which optimised power supply performance. The DC-AC inverter subsystem adjusted output voltage and frequency, adapting to different loads and enhancing system reliability. The simulation model effectively predicted wind energy utilisation, simulated various operational modes, and optimised mechanical and electrical power balance. It minimised energy losses, ensuring efficient operation of autonomous systems.

Further research is expected to expand the autonomous energy supply system for consumers by integrating additional energy sources, such as solar panels, to create hybrid autonomous energy supply systems with the possibility of effective interaction between different energy sources.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Автономна система енергозабезпечення споживачів

Анотація. Метою дослідження було розробити структуру імітаційної моделі системи автономного енергопостачання для споживачів, яка включає підсистеми моделей вітротурбін і генераторів змінного струму, а також описати характеристики її компонентів. Розглянуто порядок функціонування компонентів системи автономного електропостачання споживачів, а також особливості їх взаємодії. Імітаційна модель системи автономного електропостачання споживачів створена в програмному середовищі Simulink (Matlab) з використанням стандартних та спеціалізованих блоків бібліотеки Simulink, що дозволить найбільш наочно та детально відобразити механізми взаємодії об'єктів в автоматизованій системі електропостачання споживачів та проаналізувати отримані результати. Розроблено імітаційну модель автономної системи енергопостачання споживача, підсистеми моделей вітрової турбіни та генератора змінного струму. Детально описано отриману імітаційну модель та її основні компоненти. Для забезпечення максимальної ефективності перетворення енергії вітру в електроенергію створено модель універсального підвищувально-знижувального перетворювача напруги AC-DC_MPPT_Wind з функцією підтримання точки максимальної потужності, який виконував функції навантаження вітротурбіни та зарядного пристрою, і вихід якого підключено до акумуляторної батареї. Особливостями моделі підсистеми DC-AC_inverter є можливість регулювання вихідної напруги та частоти струму, а також вибору режиму моделювання вихідного струму - змінного або постійного, залежно від характеру дослідницьких завдань. Також описано та проаналізовано експеримент, проведений з використанням цієї моделі. Результати показали, що імітаційна модель системи автономного електропостачання споживачів працювала коректно і виконувала всі задані функції. Отримані результати можна використати на промислових підприємствах для забезпечення енергетичної незалежності та зниження витрат на електроенергію

Ключові слова: імітаційна модель; енергетична незалежність; джерела вітрової енергії; електроенергія; вітрогенератор