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Modelling the optimal switching scheme of the Ukrainian power grid during blackout (Volyn region)

Abstract. The relevance of the study, in particular, in the Volyn region, is due to the need to ensure the reliability and efficiency of the energy infrastructure in the face of growing challenges associated with the war between Russia and Ukraine, technological development and ensuring the country's energy security. The purpose of the study is to develop a model of the optimal switching scheme for the Volyn region's power grids during blackout to minimize the negative consequences and ensure priority power supply to critical facilities. The methods used include mathematical modelling, simulation, optimization, sensitivity analysis, and others. The study optimized the power grid switching scheme under the risk of war and other crisis situations, including a thorough analysis of various options in the event of a blackout. Taking into account additional aspects of grid safety and reliability, the optimal routes for power transmission, placement of backup power sources were identified and effective algorithms for grid management were developed. By optimizing the grid switching

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scheme, the damage caused by blackouts can be minimized, and power supply can be restored quickly. The results confirmed that an optimal switching scheme can significantly reduce blackout time and its impact on the economy and the lives of the population. The development of optimal switching schemes for power grids is an important step towards increasing the resilience of Ukraine's electricity system to crisis situations. The study has highlighted the importance of developing such models to ensure energy security and resilience of the power grid under the threat of blackouts, which affects the practical aspects of power supply management and economic development. The practical significance of the study is to improve strategies for managing the power grid in blackout conditions, contributing to the resilience of energy systems and economic development

Keywords: stability of electricity supply; emergencies; consumption measurement schedule; load analysis; blackout risk assessment

INTRODUCTION

The study of the optimal grid switching scheme during a blackout in Ukraine is an extremely important task in the current energy environment. Blackouts can lead to serious consequences for the economy, security, and public health, so it is important to actively work on developing and optimizing models aimed at minimizing their impact and ensuring reliable power supply to critical facilities. Given the growing threats from the war with Russia, effective strategies for managing the power grid in the face of unpredictability are becoming an urgent necessity. Research in this area will not only help to understand the risks and potential threats to the energy system, but will also contribute to the development of practical solutions for their effective management in times of uncertainty and emergency.

The relevance of the study is manifested in the consideration of the possibility and realism of scenarios where the energy system is subjected to constant shelling, especially in frontline areas. Even if an effective blackout prevention system is in place, these areas remain vulnerable to the constant threat of shelling, which can cause interruptions in power supply and negatively affect the safety and lives of the local population. In addition, the study focuses on the protection of critical infrastructure such as hospitals, water supply and transport hubs, which are vital for the functioning of society in times of crisis. The problem is the lack of effective measures to protect the power grid from such situations, which requires the development and implementation of power grid management strategies that consider the worst-case scenario of constant shelling. This research approach will help to identify opportunities and limitations in managing the power grid under continuous threat, which will allow developing effective measures to ensure the sustainability of energy supply and public safety in the context of military conflicts.

According to the study by S. Denisyuk *et al.* (2022), it is crucial to consider the impact of renewable energy sources on grid resilience and develop strategies to overcome the challenges associated with them. However, the study does not focus on optimizing the grid switching scheme in the context of war and crisis situations. In the study by D. Ostrenko & O. Kollarov (2022), the main emphasis is on the importance of using artificial intelligence to improve the efficiency of grid management. However, the paper does not study the various options for action in the event of a blackout, which is necessary for a thorough analysis. In conformity with the study by S. Kiyko *et al.* (2022), the implementation of energy efficiency strategies has the potential to improve competitiveness and sustainability in the industrial sector. However, the study does not cover additional aspects of grid security and reliability.

A study by S. Matyakh *et al.* (2021) highlights global trends in the use of solar energy and their impact on the energy sector. However, it does not analyse the optimal routes for energy transmission and the placement of backup power sources. Researchers A. Oleshko & K. Pavlyuk (2022) highlight the importance of using smart technologies to improve the security of energy supply in urban areas. However, the study does not investigate effective algorithms for managing the power grid in crisis situations. The paper by S. Onyshchenko *et al.* (2023) raises the important issue of developing effective models for managing the power grid in blackout conditions as a key task for ensuring the country's energy security. However, the study does not consider the possibility of reducing the blackout time and its impact on the economy and life of the population, provided that an optimal switching scheme is implemented.

The purpose of this study is to create an optimal model for switching the power grid in Volyn region during blackout to reduce the negative consequences and ensure priority power supply to critical facilities.

MATERIALS AND METHODS

The mathematical modelling method helped to calculate the optimal parameters of the power grid, determine the system's capacity and reserves, and predict the impact of various blackout scenarios on the operation of the power grid. Modern mathematical methods, such as linear programming, dynamic programming, and optimization theory, made it possible to consider complex interactions between different components of the system and find optimal solutions for managing power supply. Mathematical modelling has also made it possible to assess risks and develop grid management strategies that will be most effective in blackout conditions.

The use of simulation methods made it possible to recreate various blackout scenarios and conduct a detailed analysis of their impact on the operation of the power grid. This method made it possible to simulate different scenarios and test different strategies for managing power supply in contingency situations. Simulation models can take into account various factors, such as weather conditions, technical condition of the power grid, electricity demand, and others, which allowed for comprehensive research of the situation and informed decisions on power grid management. Supervisory Control and Data Acquisition (SCADA) was used for modelling and simulation of power grids in the study. This software package provided a user-friendly interface for developing mathematical models and simulations.

The optimization method allowed us to find optimal solutions for managing the power grid in blackout conditions. This method was to identify the most effective parameters and strategies that ensure maximum reliability and efficiency of the power supply system. The use of optimization methods allowed us to find the optimal allocation of resources, determine the best time to activate backup power sources, and develop optimal strategies for restoring power supply after a blackout. This method helped reduce energy consumption, ensure system stability, and reduce the risk of emergencies. The application of the sensitivity analysis method made it possible to determine the impact of changes in the initial parameters on the results of modelling and controlling the power grid during blackout. This method helped to identify key factors that affect the effectiveness of management strategies and take them into account in the decision-making process. The sensitivity analysis helped identify the most critical system parameters and their interrelationships, which contributed to the development of more accurate and reliable grid management models. The sensitivity analysis helped identify the most critical system parameters and their interrelationships, which led to the development of more accurate and reliable grid management models.

Stochastic modelling methods were used to study random variables and uncertainty in the power supply system during blackouts. This method made it possible to take into account the probability of different scenarios and consider their impact on the operation of the power grid. The use of stochastic modelling methods helped to assess risks and develop management strategies that would be most effective under conditions of uncertainty. This method helped to consider various factors, such as changes in energy demand, weather conditions and the technical condition of equipment, and to consider their impact on the operation of the grid. The application of the system analysis method helped to study the power grid as a complex system with numerous interconnected components and processes. This method made it possible to consider the power supply system as an integral structure, considering the interaction between its various components. The application of system analysis helped to identify key links and dependencies between different elements of the system and understand their impact on the operation of the power grid in blackout conditions. This method allowed us to develop comprehensive management strategies that would be the most effective and optimal for ensuring the resilience and reliability of the power grid.

The Markov process method was a powerful tool for modelling and analysing stochastic processes. It was based on the Markov property, which implied that the future state of a system depended only on its current state, not on previous states. In this study, the Markov process method was used to model transient processes in the power grid and to analyse their dynamics during blackouts. Formula of the Markov process method (1):

$$P(X_{n+1}=x|X_n=x_n, X_{n-1}=x_{n-1}, \dots, X_0=x_0)=P(X_{n+1}=x|X_n=x_n), \quad (1)$$

where $P(X_{n+1}=x|X_n=x_n, X_{n-1}=x_{n-1}, \dots, X_0=x_0)=P(X_{n+1}=x|X_n=x_n)$ – the conditional probability of transition to state x at time n + 1, provided that the system is in state x_n at time n, x_{n-1} at time, N - 1, and so on up to x_0 at time 0; X_n – the state of the system at time n, x is a specific state of the system; n is the time.

The Monte Carlo method was an effective tool for numerical modelling of complex systems or processes using random variables. By using random variables, this method allowed the evaluation of various model parameters and their impact on the results. In this study, the Monte Carlo method was used to study the sensitivity of the power grid to various parameter changes during blackouts. The formula for the Monte Carlo method to assess the sensitivity of the power grid to various parameter changes during blackout is presented as follows (2):

$$\widehat{I} = \frac{1}{N}\sum_{i=1}^{N} f(x_i), \quad (2)$$

where $\widehat{I}$ – an estimate of the expected value of the performance indicator or model result; N is the number of iterations used in the Monte Carlo method; $f(x_i)$ – the value of the function or performance indicator for each iteration i; x_i – a random variable generated at the i-th iteration.

This formula allows estimating the expected value of a certain parameter or modelling result using random variables and the average value of N iterations.

RESULTS

Modelling the optimal switching scheme for power grids during a blackout is a key aspect of ensuring the resilience and efficiency of power supply in emergency situations. This complex technical process requires an integrated approach and consideration of various factors affecting the power grid. The modelling needs to take into account the availability of resources such as generating capacity and network equipment, as well as the needs of consumers at different times (Venkatanagaraju & Biswal, 2022). In addition, it is important to consider possible risks and constraints, such as transmission line capacity constraints and potential equipment failures. Only by carefully analysing these factors can an optimal switching scheme be developed that will ensure a reliable and efficient power supply during a blackout. Block diagram of power grid management considering unforeseen situations (Fig. 1).

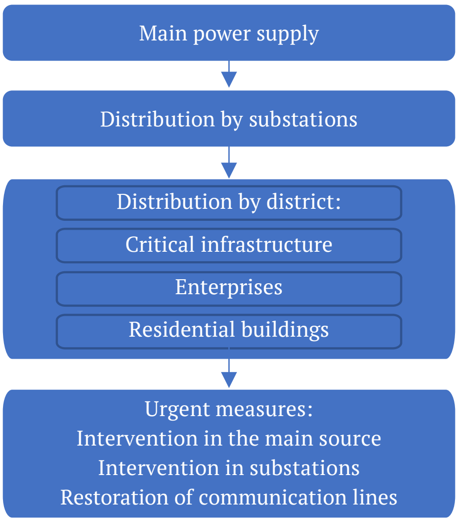

Figure 1. Optimal switching scheme for power grids during a blackout

Source: compiled by the authors

In this block diagram, the main power source is located at the top. From this source, power is supplied to substations, which in turn transmit electricity to different areas. The districts are divided into several categories, including critical infrastructure, businesses, and residential buildings. In the event of unforeseen situations that could lead to a crisis, urgent measures must be taken. These measures include intervening in the main power source to address the problem directly at the power source, intervening in substations to address problems at the level of power redistribution, and restoring communication lines and other critical facilities that may be disrupted by the crisis.

The scheduling of regional real consumption metering is an important component of effective grid management. This process determines the time and resources required to collect data on electricity consumption in different areas of the region. Taking into account geographical, weather and other factors, the metering schedule ensures that the data on the actual load on the grid is representative. This data is key for effective planning and management of the power system, helping to ensure the stability of electricity supply, optimize grid operation and maintain a balance between electricity generation and consumption. Considering the dynamics of electricity consumption and changes in grid operating conditions, the schedule for measuring real consumption in the regions allows us to respond effectively to changes and ensure reliable electricity supply for consumers. Electricity is generated in the Volyn region's power grid by a variety of sources, including: Rivne Nuclear Power Plant (NPP), which has a capacity of 4,400 MW and is the largest generating facility in the region; Dobrotvir Thermal Power Plant (TPP), which is coal-fired and has a capacity of 1,950 MW; and Lutsk Combined Heat and Power Plant (CHP), which generates 180 MW of electricity and heat for the city of Lutsk; Several small hydroelectric power plants (HPPs) are located in the region, with a total capacity of about 50 MW; The renewable energy sector includes solar and wind power plants, which are actively developing in the region. The capacity of such plants is constantly growing, which helps to reduce dependence on traditional energy sources.

Electricity from the generating facilities in Volyn Oblast is transported to distribution substations through a network of high-voltage power lines (HVL). The transmission line network includes lines of different voltages: 330 kV transmission lines stretch over 500 km and connect Rivne NPP, Dobrotvir TPP and other key energy facilities. 110 kV power lines stretch over 2,000 km and distribute power across the region. 35 kV power lines stretch over 5,000 km and supply cities and towns with electricity to meet their needs. Electricity supplied by distribution substations is transported to end consumers through a network of low-voltage power lines. The network of low-voltage power lines includes lines of different voltages, in particular: 10 kV power lines with a length of over 10,000 km. These lines supply electricity to homes, businesses, and other facilities, meeting their electricity needs (Guo *et al.*, 2023).

Electricity generated in the Volyn region's power grid is distributed among different categories of consumers. Industrial enterprises take the largest share – 40% of the total consumption. Residential consumers use 30% of electricity, in particular, for lighting, heating and household needs. Agriculture consumes approximately 10% of electricity, using it for irrigation, processing, and other needs. Other sectors such as transport, street lighting, utilities consume the remaining 20%. This distribution of consumption allows for optimized use of electricity and ensures the efficient functioning of the grid (Fig. 2). Negative scenarios that could occur in the Volyn region's power grid could lead to serious interruptions or even a complete system failure. Some of these include: accidents at power plants, such as generator failure, fire or explosion, which could lead to a suspension of electricity production and cause supply shortages; damage to transmission lines due to natural disasters or accidents, such as storms, ice, line breaks or cable theft, which could disrupt the transmission of electricity to consumers; increased consumption, which could cause peak loads or abnormally low temperatures that exceed the network's capacity. In addition, shelling could adversely affect the power grid, which could result in damage to power lines and infrastructure, as well as blackouts in certain areas.

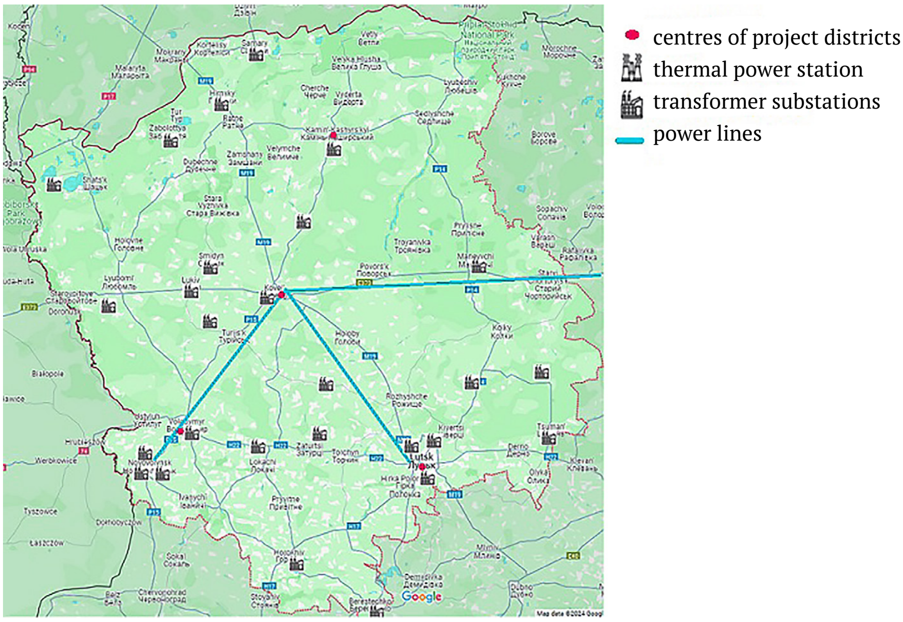

Figure 2. Power plants in the Volyn region

Source: created by the authors

Data collection involves the systematic and comprehensive collection of information about the structure, components, and characteristics of the power grid for the purpose of further analysis and identification of optimal solutions. The main objective of data collection is to obtain comprehensive information about all components of the power grid, including generating facilities, distribution lines, substations, transformers, consumers, and other important elements. Data on power, voltage, current, electricity consumption, and technical parameters of each component provide a complete picture of the grid's functioning (Panda & Das, 2021). Data collection can be done through a variety of sources, such as archival records, technical documentation, on-site measurements, specialized databases, and reports and statistics from energy companies and regulators. An important part of the data collection process is its systematization and analysis, which allows us to identify the main trends, problems, and opportunities in the development of the electricity grid. The accuracy and completeness of the data collected determines the quality of further research and the adoption of informed decisions on optimization and modernization of the power grid.

Grid load analysis involves estimating the expected load on the grid at different times of the day, considering various factors that may affect electricity consumption. It is necessary to take into account the peak load, which reflects the maximum amount of electricity consumption in a certain period of time (Rahman *et al.*, 2021). This usually refers to the peak hours when electricity demand reaches its maximum due to high consumption by households, industry, and other sectors of the economy. Peak loads can be predicted based on historical consumption data and other factors such as weather and economic activity. In addition, it is necessary to analyse the normal load, which reflects the average level of electricity consumption during the day or week. This allows for effective planning of electricity generation and distribution to ensure the most efficient use of resources. It is important to take into account the impact of weather conditions and seasonal variations on the load on the grid. For example, higher temperatures in the summer can lead to an increase in electricity consumption for air conditioning, and seasonal consumption can also affect electricity demand.

Blackout risk assessment is an important step in ensuring the reliability and efficiency of electricity supply in Volyn region. Investigating potential causes of blackouts allows us to identify factors that can cause a sudden loss of electricity supply (Carreras *et al.*, 2021). These may include technical failures, natural disasters, high network load, and equipment malfunctions. In addition, it is important to consider the possible consequences of blackouts for the grid and consumers. These consequences may include loss of productivity of enterprises, disruption of critical systems, as well as negative economic and social consequences for the population. In the current political environment, especially in the context of the war with Russia, the risk of blackout is growing significantly. Military actions may result in damage to the power grid due to shelling, attacks on energy facilities or interference with the operation of power supply systems. In addition, the possibility of a temporary interruption in the supply of gas or other resources required for power generation in the event of a military conflict could significantly complicate the situation with electricity supply. Thus, assessing blackout risks in the context of military conflict is extremely important for developing effective measures to protect and ensure the reliability of electricity supply not only in Volyn region, but also in Ukraine as a whole. A stochastic model takes into account randomness or uncertainty in a system, allowing for random changes or variations in input parameters or conditions. One of the widely used methods for building stochastic models is the Markov process method (1). Identification of these risks helps to develop strategies for prevention and effective management in emergency situations, which helps to ensure the reliability of electricity supply and protect the interests of consumers in Volyn region.

The development of a switching plan involves the development of a detailed action plan for the efficient disconnection and connection of power lines and substations in order to minimize interruptions in power supply and ensure maximum availability of electricity to consumers. In developing a switching plan, an important step is to determine the sequence of disconnection and connection of power lines and substations. This requires analysing the structure of the grid, the capacity of different lines and substations, and the needs of consumers at different times of the day and operating conditions. Specific criteria should be developed for switching lines and substations on and off. This may include assessing the capacity, condition, and load of each facility, as well as deciding on priorities for supplying critical facilities such as healthcare or emergency services (Bohra & Anvari-Moghaddam, 2022). Testing and improving the developed switching plan by simulating various blackout scenarios and implementing the necessary adjustments, taking into account the identified shortcomings and requirements for effective grid management in emergency situations.

Modelling of the power grid system was an important step in the process of developing and testing the effectiveness of the blackout switching plan. The use of specialized modelling software allowed for a detailed analysis of the developed plan and identification of its best parameters to ensure reliable power supply in unforeseen situations. Sensitivity analysis is used to determine the impact of changes in parameters on the model output. The main purpose of sensitivity analysis is to identify and quantify the impact of parameter variations on the model output. This can be done using a variety of methods, such as analytical or numerical approaches, or the use of appropriate software. One of the most common methods is the Monte Carlo method (2). This method is based on randomly selecting values of the input parameters of the model and repeating the model calculations for each random choice. Then the results of each calculation are averaged to obtain an estimate of the efficiency indicator or other model parameter. This approach allows evaluating the system's behaviour under a wide range of random conditions and considering their impact on the modelling results. The system modelling involved the creation of a virtual model of the power grid, which reflected all the main components of the system, such as power lines, substations, transformers, and their interconnections (Hoang & Nguyen, 2021). Based on this model, various blackout scenarios were simulated, and the switching plan was tested to see how it performs in real-world conditions. Next, different blackout scenarios were simulated and the impact on the grid was analysed. This included estimating the time to restore power supply, identifying possible overload points, and developing strategies to avoid them. After the simulation was completed, the efficiency and reliability of the developed switching plan was assessed. This allowed identifying its advantages and disadvantages, as well as making the necessary adjustments to ensure the optimal functioning of the power supply system in emergency situations.

By analysing the grid and its parameters, it is possible to improve the plan to minimize power losses and maximize energy availability to consumers (Mansouri *et al.*, 2021). This may include identifying suboptimal sequences of power line and substation disconnection and connection that lead to unnecessary power losses or limit energy availability to consumers. Next, strategies need to be developed to address the identified deficiencies and improve the switching plan. This may include optimizing the sequences of disconnection and connection, developing new criteria for making decisions on the operation of lines and substations in blackout mode, and using new technologies and methods of grid management. Validation and verification of the optimized switching plan using simulation methods and testing it on real data is an important step. This allows making sure of its effectiveness and reliability before implementing it in practice. To develop a model for urgent response to grid crises, such as blackouts, an algorithm can be used that will be able to respond quickly to problems and provide effective solutions to restore system operation. This algorithm can be implemented using software based on artificial intelligence, machine learning, and control systems such as SCADA systems. Continuous improvement and updating of the switching plan is a necessary component in ensuring efficient and reliable power supply in blackout conditions. The algorithm must constantly monitor the state of the grid and detect any signs of a crisis situation, such as overloads, circuit outages, consumption anomalies. Once a problem is detected, the algorithm should assess the severity of the situation, determine its priority and potential consequences. Based on the situation assessment, the algorithm should make a quick decision to activate the necessary measures to immediately restore the grid. The algorithm must ensure effective communication with all relevant parties, such as grid operators, rescue services, government agencies, and coordinate their actions to respond quickly and effectively to the crisis situation. The algorithm should automatically perform the necessary measures, such as disconnecting the load, switching on backup power sources, switching the power grid, to restore the system. After the system is restored, the algorithm should continue to monitor the state of the power grid and make necessary updates to prevent similar crisis situations in the future.

Improving the switching plan involves analysing the effectiveness of its operation in real conditions, identifying possible shortcomings, and identifying new opportunities to optimize grid management processes (Khismatullin & Bashirov, 2021). This may include revising the sequences of disconnection and connection, updating the technical parameters of equipment, and introducing new technologies and control methods. Updating the switching plan is also important to take into account changes in the structure of the grid, such as an increase or decrease in the number of substations, transmission lines and consumers. New technologies and the development of alternative energy sources may also affect the efficiency and reliability of power supply planning.

DISCUSSION

Modelling the optimal blackout switching techniques for Volyn Oblast proved to be an important step in the region's readiness to manage energy crises. The analysis provided important data on the grid structure and load, as well as identified potential blackout risks. In particular, it identified critical points in the grid, such as overloaded lines and substations, which could cause accidents in the event of an emergency. On this basis, specific switching strategies were developed to reduce blackout risks and ensure a stable power supply for consumers. The use of specialized software tools made it possible to simulate various blackout scenarios and evaluate the effectiveness of the developed switching plan. The use of SCADA for modelling and simulation of power grids in the study provided a convenient interface for developing mathematical models and simulations. This helped to identify the advantages and disadvantages of the plan, as well as to improve it in order to increase reliability and efficiency. The results of the study confirmed the importance of modelling optimal switching strategies for power grids in solving energy security problems and ensuring stable power supply during emergencies. Given the ever-increasing challenges, such research is becoming an integral part of power grid management and ensuring the country's energy security.

According to the results of recent studies by F. Kebede *et al.* (2021), assessing the reliability of renewable energy systems by modelling power outages in distribution networks is a key step in ensuring the stability and continuity of electricity supply. This approach allows us to assess the efficiency and reliability of the system in unforeseen situations, such as accidents, emergencies, or blackouts. Power outage modelling helps identify weaknesses and potential problems in the grid, which helps develop strategies to improve reliability and restore supply in emergency situations. These data are consistent with the theses presented in the previous section. In particular, the modelling allows for the analysis of different power outage scenarios and their impact on the operation of the restoration system. This can include estimating the time to restore power supply, identifying possible overload points, and developing strategies to avoid them. Modelling also allows for an analysis of the effectiveness of measures to ensure reliable power supply in emergency situations, which helps to improve response plans and backup strategies.

Referring to the definition of D. Ivanov (2022), a power outage can trigger a chain reaction throughout the supply chain. This is due to the interstructural ripple effect, where power outages affect other sectors and industries. For example, a shutdown of power plants can lead to a halt in production at industrial enterprises, increased machine downtime and loss of productivity. An analysis of the impact of power outages on productivity shows that long interruptions in power supply can significantly reduce the efficiency of the production process. Uninterrupted power supply is key for many industries, such as manufacturing, healthcare, transport, and others. Losses in productivity can have serious economic consequences and lead to losses for businesses and society as a whole (Kuznetsov, 2024). It is worth noting that the resilience and viability of the electricity supply system become essential aspects in the face of interruptions. Developing and implementing measures to improve grid resilience, such as backup power supplies, emergency recovery plans and network system improvements, can help reduce the system's vulnerability to interruptions and increase its resilience in the face of unforeseen events (Ali *et al.*, 2022).

Researchers F. Mohamad *et al.* (2021) identified that the optimal planning of microgrids for sustainable distribution networks is a key challenge in modern energy infrastructure, especially in the context of growing challenges such as climate change and the increased use of renewable energy sources. Microgrids are small, self-sufficient systems that can function as standalone units or be integrated into the general power grid. Optimal planning of microgrids includes determining the optimal network size, location, and distribution of resources, including renewable energy, storage systems, control, and protection systems. This requires a coherent approach to the technical, economic, and environmental aspects of planning, taking into account the needs of consumers and the requirements for the sustainability and reliability of electricity supply. Optimal planning of microgrids contributes to the efficiency and resilience of distribution networks, reducing energy losses and increasing the use of renewable energy sources (Korduba, 2022). These results support the above study as they highlight the importance of optimal microgrid planning to ensure the resilience and efficiency of distribution networks. Taking into account technical, economic and environmental aspects allows determining the most optimal solutions for the size and location of microgrids, as well as the efficient use of resources, including renewable energy. This approach helps to reduce energy losses and improve the overall reliability of electricity supply, especially in the face of growing challenges associated with climate change and the expansion of renewable energy sources.

Researchers K. Liang *et al.* (2024) have shown in their work that the restoration of the power system with a high penetration of renewable energy sources is an important aspect of the development of modern energy, which is mostly a complex process. Today, the high penetration of renewable energy sources, such as solar and wind energy, creates new challenges and opportunities for the energy system (Stoliarov, 2024). The current state of play is the gradual introduction of renewable energy sources into the energy system, which contributes to reducing dependence on traditional sources such as coal and oil and reducing greenhouse gas emissions. Future trends in grid renewal include further increases in renewable energy generation, development, and improvement of energy storage technologies, improvement of infrastructure to support decentralized grids, and increased efficiency and reliability of the grid as a whole (Selvakumar *et al*., 2024). The authors of this study can agree with this opinion that the development of modern technologies and the increase in environmental awareness of society contribute to the activation of these trends and contribute to the formation of an energy system based on the use of renewable energy sources and demonstrating a high level of sustainability and resistance to external influences.

As noted by G. Fotis *et al.* (2022), the risks in the European electricity transmission system are becoming increasingly apparent in the face of growing complexity and instability driven by both external and internal factors. Large-scale power outages can occur for a variety of reasons, including technical problems, natural disasters, cyber-attacks, or manufacturing deficiencies. These outages can have serious consequences for the economy, security, and comfort of citizens. In this regard, the development of a new power system restoration strategy becomes extremely important to ensure the stability and reliability of electricity supply (Selvakumar *et al*., 2023). Analysing the results and conclusions, a new strategy for restoring the power system after a major power outage requires a comprehensive approach that considers various aspects of the energy infrastructure and the challenges it faces. It may include rapid identification and localization of problematic areas of the grid, effective management of reserve capacity, strategies for restoring power supply, and customer engagement to ensure maximum recovery efficiency. It is also important to use advanced technologies and analytical tools to predict and manage major outages, which allows for a prompt response to situations and minimizes their impact on the energy system and society as a whole.

Researchers S. Ghasemi *et al.* (2021) determined that the new predictive restoration of critical loads in distribution networks reflects modern requirements for energy management systems in emergency situations. Considering the load curve of critical consumers, this strategy is focused on ensuring priority restoration of power supply to the most important objects for society, such as medical facilities, emergency services, and infrastructure that ensures safety and vital services. This strategy is based on the analysis of data on electricity consumption by different categories of consumers at different times of the day and load conditions. It uses advanced forecasting and modelling algorithms to identify critical loads and their real-time power supply needs. This allows us to respond quickly to power outages and restore power to the most important places for society, ensuring the continuous operation of critical facilities and reducing the impact of unforeseen situations on public health and safety. In addition, the application of a new strategy for the predictive restoration of critical loads can contribute to the efficient use of resources in response to energy crises and emergencies. Through automated analysis and management, systems can respond quickly to power outages and mobilize the necessary resources to restore supply in critical areas.

CONCLUSIONS

Modelling the optimal switching scheme of the Ukrainian electricity grid is an important step in ensuring stable electricity supply and avoiding possible power losses for consumers in the event of a blackout. Studies have shown that effective modelling can lead to the development of an optimal switching strategy that maximizes energy availability for consumers and minimizes supply interruptions. The schedule for measuring real electricity consumption has proved to be a key component for effective grid management. Analysis of the collected consumption data allowed us to understand the dynamics of electricity demand in different periods and conditions. This data was necessary to develop grid management strategies and plan its development. The efficient allocation of time for consumption measurement has led to a reduction in energy losses and an increase in the reliability of electricity supply. Constant updating and analysis of this data helped identify trends and problems in the operation of the grid, which in turn allowed for prompt response and improvement of the power supply management system.

The use of specialized software tools, including SCADA, made it possible to conduct a detailed analysis of the structure and capacity of the power grid, as well as to identify critical facilities that require the highest priority in ensuring power supply in the event of a blackout. This contributed to efficient resource management and quick response to unforeseen situations. Moreover, the modelling helped to improve management strategies and the optimal use of backup energy sources during crisis situations. This made it possible to identify weaknesses in the system and develop effective measures to address them. The use of real-world power grid switching models plays an important role in improving the reliability of power supply and ensuring the stability of the energy system during crisis situations. This approach helps to effectively address energy security issues and increases the level of protection of the population and the economy from the negative effects of blackouts, ensuring stable power supply even in the most difficult conditions.

Additional research could include analysing the effectiveness of the proposed switching plan in real-world conditions and improving the methods of managing power grids to take into account changes in the energy system and societal needs.

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CONFLICT OF INTEREST

None.

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Моделювання оптимальної схеми перемикання електромереж України під час блекауту (Волинська область)

Анотація. Актуальність дослідження, зокрема у Волинській області, обумовлена необхідністю забезпечення надійності та ефективності енергетичної інфраструктури в умовах зростаючих викликів, пов’язаних з війною Росії та України, технологічним розвитком та забезпеченням енергетичної безпеки країни. Метою дослідження є розробка моделі оптимальної схеми перемикання електромереж Волинської області під час блекауту для мінімізації негативних наслідків та забезпечення пріоритетного електропостачання критично важливих об’єктів. Серед використаних методів слід виділити метод математичного моделювання, симуляційний метод, метод оптимізації, метод аналізу чутливості інші. У дослідженні було проведено оптимізацію схеми перемикання електромережі в умовах ризику війни та інших кризових ситуацій, зокрема, ретельний аналіз різних варіантів дій у випадку блекауту. Враховуючи додаткові аспекти безпеки та надійності електромережі, було визначено оптимальні маршрути передачі енергії, розміщення резервних джерел живлення та розроблено ефективні алгоритми керування електромережею. Завдяки оптимізації схеми перемикання електромережі можна мінімізувати шкоду від блекаутів та забезпечити швидке відновлення електропостачання. Результати підтвердили, що оптимальна схема перемикання може значно зменшити час блекауту та його вплив на економіку та життя населення. Розробка оптимальних схем перемикання електромереж є важливим кроком до підвищення стійкості електроенергетичної системи України до кризових ситуацій. Дослідження підкреслило важливість розробки таких моделей для забезпечення енергетичної безпеки та стійкості електромережі в умовах загрози блекауту, що відображається на практичних аспектах управління електропостачанням та забезпеченні економічного розвитку. Практичне значення дослідження полягає у вдосконаленні стратегій управління електромережею в умовах блекауту, сприяючи підвищенню стійкості енергетичних систем та економічного розвитку

Ключові слова: стабільність електропостачання; надзвичайні ситуації; графік вимірювання споживання; аналіз навантаження; оцінка ризиків знеструмлення