Machinery & Energetics
Vol. 15, No. 4. 2024

Journal homepage:
https://technicalscience.com.ua/en

UDC 621.31:004.94
Doi: 10.31548/machinery/4.2024.69

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

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

Article's History: Received: 26.07.2024; Revised: 01.11.2024; Accepted: 27.11.2024.

Suggested Citation:
Mikhailova, L., Dubik, V., Kozak, O., Dumanskyi, O., & Gorbovy, O. (2024). Modelling the optimal switching scheme of Ukrainian power grids during blackout in one city/region. *Machinery & Energetics,* 15(4), 69-81. doi: 10.31548/machinery/4.2024.69.

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

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

INTRODUCTION

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

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

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

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

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

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

MATERIALS AND METHODS

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

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

RESULTS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

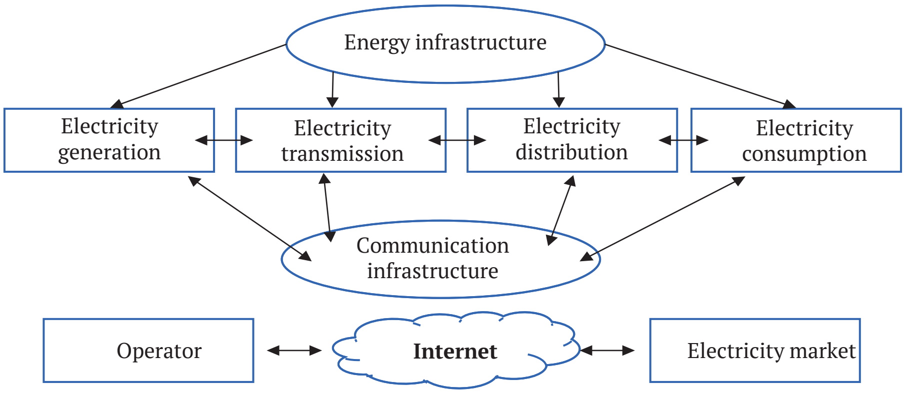

Figure 1. Interaction of elements of a smart electricity system
Source: compiled by the authors based on C. Kaur *et al*. (2024)

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

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

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

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

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

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

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

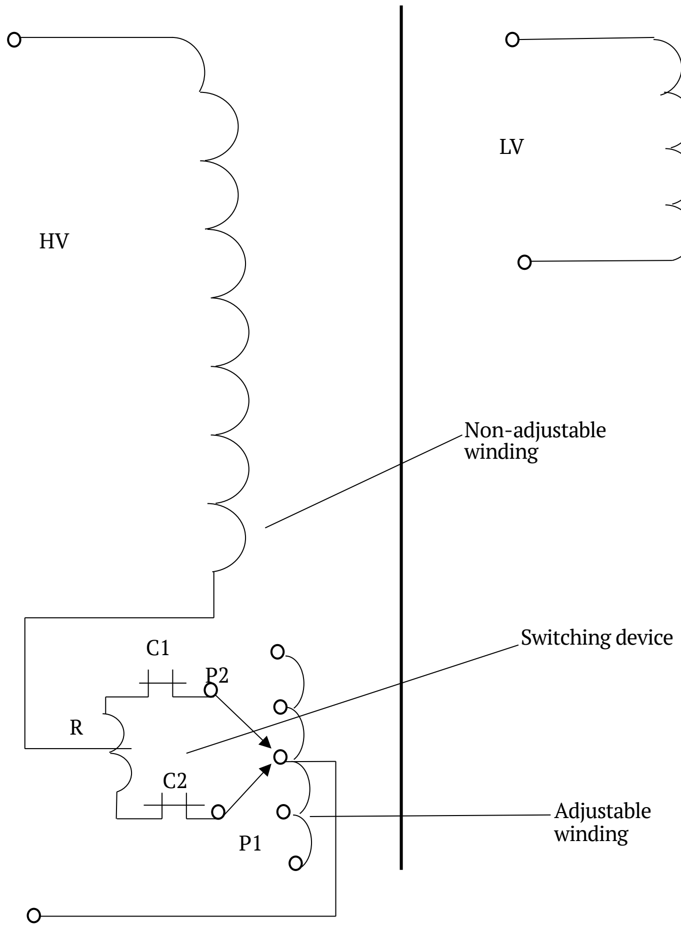

Figure 2. Voltage control circuit for transformers with two windings
Note: HV – high voltage, LV – low voltage, C1 and C2 – commutators, R – regulating device, P1 – primary winding, P2 – secondary winding
Source: compiled by the authors based on G. Liobikienė *et al*. (2024)

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

DISCUSSION

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

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

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

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

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

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

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

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

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

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

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

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

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

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

CONCLUSIONS

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

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

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

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

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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

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

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