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ENHANCING OF THE POWER SYSTEM RESILIENCE THROUGH THE APPLICATION OF MICRO POWER SYSTEMS (MICROGRID) WITH RENEWABLE DISTRIBUTED GENERATION

Abstract. *The power sector plays a critical role in the functioning of the economy and the security of a country, being closely interconnected with other vital infrastructures, such as gas supply, water supply, transportation, and telecommunications. Ensuring a stable power supply is crucial for the uninterrupted operation of these systems. One way to enhance the resilience of the power system is by integrating local networks with distributed renewable generation into the overall energy infrastructure. The flexibility, stability, controllability, and self-healing capabilities of microgrids make them an effective solution for improving the resilience of the power system. The power grid is susceptible to disturbances and disruptions that can cause large-scale power outages for consumers. Statistical data indicates that approximately 90% of outages occur due to issues in the distribution system, thus research focuses on local microgrids with distributed renewable generation. This study analyzed the role of microgrids with renewable generation in enhancing the resilience of power systems. Additionally, functions of microgrids that contribute to enhancing power system resilience, such as service restoration, network formation strategies, control and stability, as well as preventive measures, were summarized. It was found that local microgrids have significant potential to enhance power system resilience through the implementation of various strategies, from emergency response planning to providing reliable energy supply for quick responses to military, environmental, and human-induced crises. The concept of local distributed energy generation, storage, and control can reduce reliance on long-distance power transmission lines, reduce network vulnerabilities, and simultaneously improve its resilience and reduce recovery time. It has been determined that the most necessary and promising approaches to enhance the resilience of the power system include developing appropriate regulatory frameworks, implementing automatic frequency and power control systems, ensuring resource adequacy (including the reservation of technical components), promoting distributed generation, integrating energy storage systems into the energy grid, and strengthening cyber security.*

Keywords: resilience, local power systems, MicroGrid, distributed generation, renewable energy sources.

1. Introduction

The electric power complex is a part of critical infrastructure and serves as the basement and driving force of the economy, national security, and environmental conditions in the country. It is interconnected with other critical infrastructure components, such as gas and water supply, transportation, and communication systems. Any disruption in the power supply system directly and significantly impacts the functioning of these critical infrastructure components.

Due to massive missile attacks on the energy infrastructure, the average household in Ukraine had to endure a total of five weeks without electricity during the winter of 2022/2023 [1]. Electricity plays a vital role in all aspects of ordinary life, and its absence leads to severe consequences for communities. The lack of electricity complicates the provision of medical care, performance of various tasks, education of children, and disrupts communication processes.

The United Nations Development Programme (UNDP) along with the World Bank conducted an assessment that identified specific areas of destruction and allowed for an estimation of repair work possibilities and the required funding volume needed for infrastructure restoration. Ukraine suffered significant damages amounting to 10 billion USD, which resulted in limited access to electricity for 12 million people, damage to 22 out of 36 power stations, and destruction of parts of the district heating system in areas affected by military actions [2].

It is worth noting that the rate of recovery of the Ukrainian power system increased after each mass attack, primarily due to organized and coordinated repair work by energy industry workers at all levels. This ensured the prompt restoration of damaged power transmission lines and the repair of destroyed substations. Achieving significant recovery efficiency, the power generation system is currently in a stable state, and instances of limited electricity supply mostly occur during maintenance and repair work. Working together with distribution system operators, "Ukrenergo" successfully implemented new approaches to respond to russian missile and drone attacks on the power system [3]. These approaches are based on assimilating previous experiences, improving the organization of repair and restoration work, and achieving faster and more efficient responses to destructive events, in full compliance with global principles of enhancing power system resilience.

Ensuring the resilience of systems is one of the main trends worldwide to ensure the security of both critical infrastructure and national security as a whole. In the context of critical infrastructure security during times of war in Ukraine, the goal of ensuring safety and stability in the country can be defined as strengthening the protection of national critical infrastructure by preventing, deterring, neutralizing, or mitigating the consequences of deliberate actions by aggressor countries aimed at destroying, disabling, or exploiting critical infrastructure. The action plan to achieve this goal should involve enhancing national preparedness, timely responses, and rapid restoration of critical infrastructure in the event of an attack, natural disaster, or other emergencies [4].

2. The concept of resilience

In scientific literature, there is no universal definition of resilience, as this term is broad and encompasses many factors [5]–[7]. It can be described as the ability to effectively prepare for low-probability events with high potential impact, to timely and sufficiently withstand these events, to reduce their negative consequences, and/or to shorten the recovery period. This includes the ability to endure crises, adapt to them, address uncertainties, and recover quickly after such events.

The main characteristic of a resilient system is its ability to effectively function during all stages of crisis response in order to fulfill its intended functions. As noted in [8], due to their economic, humanitarian, and geopolitical significance, energy infrastructure facilities are particularly frequent targets of russian military aggression. Therefore, in the context of the resilience of the electric power complex, this concept can be defined as its ability to withstand disruptions and continue providing accessible energy services to consumers.

In a broader sense, the resilience of critical infrastructure refers to its ability to reduce the scale and/or duration of a destructive event. Therefore, in the context of the electric power complex, resilience implies its capacity to meet consumers' needs for services (electricity) regardless of the circumstances. This means that the system is capable of reliably functioning under normal conditions, resisting threats, adapting to constantly changing conditions, and quickly recovering after the realization of any threats (attacks, destruction, etc.).

The life cycle of resilience, developed in [9], shows in Fig. 1. It includes various stages of planning and managing resilience, including a feedback loop to incorporate lessons learned from previous events. This illustration emphasizes that resilience goes beyond reliability or the ability to recover. Resilience involves planning for and mitigating these events before, during, and after their occurrence.

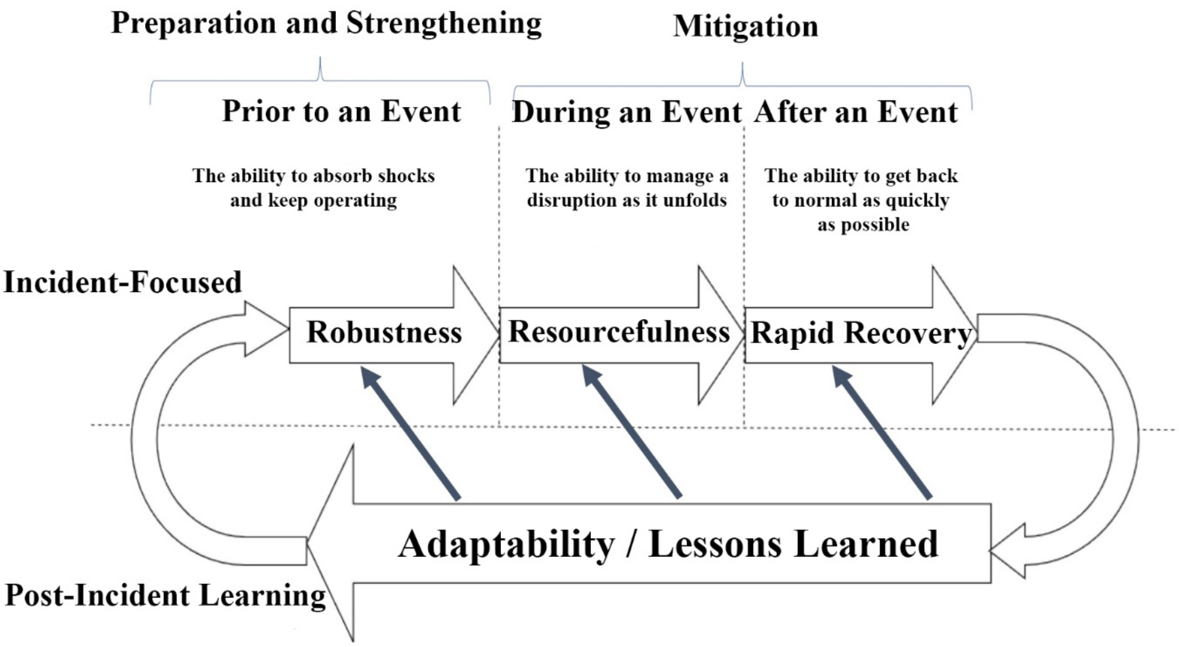

Fig. 1. Resilience Lifecycle

In an ideal scenario, the electric power system should have a structure and organization that enables it to possess the properties of elasticity: to flex without breaking, to withstand disturbances with minimal damage, and to ensure quick recovery.

3. Criteria for a crisis situation in the power sector of Ukraine

Current legislation in Ukraine provides measures for the involved entities in the management and economic activities of the power sector to respond to crisis situations. In the event of threats to the stability of Ukraine's power system, the Cabinet of Ministers of Ukraine, in accordance with established legislation, may introduce temporary "emergency measures" for the functioning of the energy market [10]–[11]. The criteria for implementing such measures include:

1. Damage to electricity facilities or unauthorized interference by third parties that may result in a reduction of electricity consumption by more than 100 MW.
2. Reduction of the reserve of energy-generating capacities in the power system of Ukraine below the permissible level for three consecutive days.
3. Critical fuel supply condition, particularly a decrease in fuel reserves at individual thermal power plants of energy-generating companies below a 20-day supply.
4. Lack of full payment for electricity for three consecutive months or payment below 90% in the billing month.

The decision to implement temporary emergency measures is made by the Cabinet of Ministers of Ukraine based on submissions from the Ministry of Energy and Coal Industry or the National Commission for State Regulation of Energy and Public Utilities. Temporary emergency measures may be imposed for a period not exceeding one month during peacetime. During this period, power sector entities, regardless of ownership form, are required to comply with the standards of operational safety of Ukraine's power system and the operational commands and directives of the Transmission System Operator "NPC "Ukrenergo."

The issue of destructive and crisis events that go beyond ordinary failures has been extensively studied in the literature, mainly focusing on the impact of natural disasters [12]–[15]. It should be noted that for Ukraine, due to its favorable geographical location and climate, it was not such an urgent task until the russian military aggression and deliberate attacks on the power sector. A comparative analysis of the characteristics of ordinary failures and destructive crisis situations in the power sector is presented in Table 1.

Table 1. Comparative analysis of characteristics of ordinary failures and destructive crisis situations in the power sector [15]

Typical (ordinary) failures	**Crisis Situations / Destructive Events**
• A single failure due to the malfunction of one component. • General analyses do not consider the stochastic component. • There is no spatial-temporal correlation for the failure - it occurs randomly. • Most generating units continue to operate and remain connected. • System-forming and distribution networks remain intact. • Only the infrastructure of the electrical grid is involved. • It is quickly repaired and restored to a working state.	• Multiple failures due to catastrophic damages. • Uncertainty and stochasticity of natural disasters or military attacks. • Spatial-temporal correlation for failures caused by crisis situations. • Generating capacities may become inoperable. • Transmission and distribution networks are damaged and insufficient. • Strong influence and interconnection with other infrastructures. • Difficult to repair and restore (e.g., consequences of a catastrophe).

4. Main characteristics of power system resilience

Power system resilience can be divided into two main categories: 1) infrastructure resilience and 2) operational resilience. Infrastructure resilience is primarily defined as the sufficient physical strength of the power system to withstand and be less susceptible to damage from major disruptions. Operational resilience relates to the continuity of operations, i.e., uninterrupted supply or adequacy of ready-to-use generating capacities despite adverse events.

Characteristics of power system resilience include aspects such as robustness, reliability, redundancy, as well as time of response and recovery speed, as shown in Fig. 2. Robustness focuses on strengthening components, reliability emphasizes designing components to work under various conditions, redundancy involves installing backup components, and time of response and recovery speed pertain to how quickly and effectively the system reacts during a failure [16].

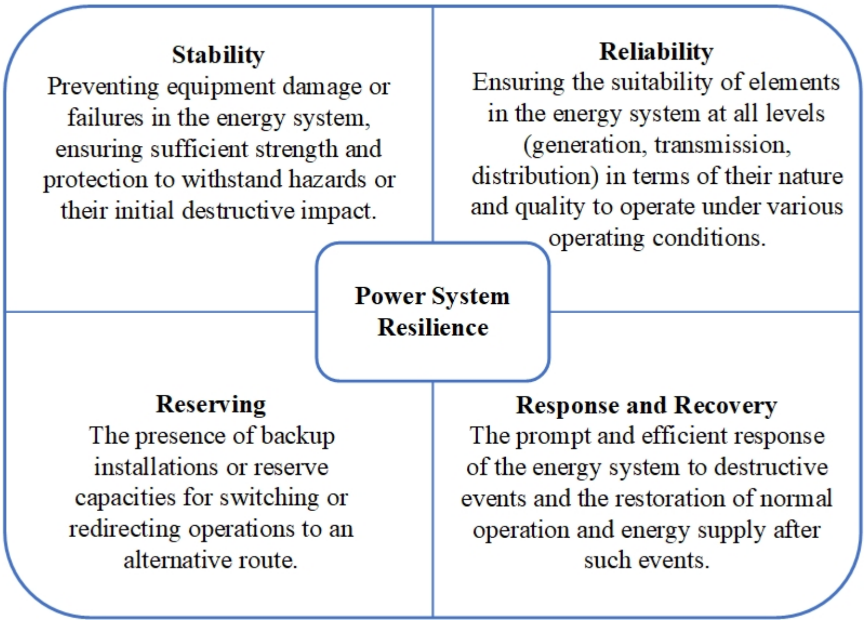

Fig. 2. Key characteristics of power system resilience

Modern power systems are implemented through a combination of various technologies, including solar energy, wind energy, energy storage, electric vehicles, smart buildings, and prosumers. All these elements can be integrated into micropower systems that can operate both in isolated mode and in parallel with the main grid. Integrating these micropower systems with intelligent sensors and energy management systems allows for efficient integration at low and medium voltage levels into existing distribution networks, ensuring their effective, reliable, and cost- benefited operation.

5. Directions to enhance the resilience of the power system

Development of physical protection systems for energy infrastructure objects. One of the key directions of resilience in wartime is the construction of physical protection systems for energy infrastructure objects, such as underground or surface shelters. Such shelters are specialized structures or areas designed to protect vital energy infrastructure from missile attacks, bombardments, terrorist acts, and other hostile actions. They can be built underground or on the surface, depending on the technical and technological characteristics of the energy object. Shelters provide a high level of protection and resilience to the object during hostile attacks, allowing for the preservation of operational capabilities and the continuation of energy services even in conflict situations. Underground bunkers are also effective means of protecting energy infrastructure objects from hostile actions. They can be used for storage and accumulation of reserve energy supplies, as well as providing shelter for personnel and critical equipment during crisis situations. Underground bunkers offer a higher level of security and resilience, reducing the vulnerability of energy objects to external threats.

The development of physical protection systems is characterized by their high cost and complexity of implementation. However, these costs are justified by the critical importance of ensuring the stability and security of energy infrastructure facilities, especially in wartime, under the conditions of increasing threats of missile attacks as well as terrorist acts.

Application of automatic frequency and power regulation system. Frequency is an important parameter that determines the quality of electrical energy and the stability of the power system. Maintaining a balance of power between generation and consumption is crucial for ensuring system reliability [17]. Frequency regulation is a critical tool for supporting the stability and reliability of the power system, which directly influences its resilience.

Segmentation and infrastructure redundancy. Component failures during destructive events are a common occurrence. Under extreme conditions, the probability of multiple components failing simultaneously increases. However, system resilience can be ensured through redundancy, prevention of sequential cascading failures, and designing the system with smooth power reduction in the event of individual component failures. Another effective strategy is segmentation, which limits the impact of faults or short circuits to specific sections without affecting others. Redundancy, although costly, remains a prevalent method for mitigating the consequences of equipment failure. Duplicate power transmission lines from different substations also ensure reliable electricity supply.

Development of energy storage systems. Energy storage has the potential not only for storage purposes but also for improving the quality and reliability of distribution networks. Energy storage systems can perform various functions, such as accumulation, storage, and providing additional services to the power system. These energy storage systems can contribute to frequency stabilization, voltage regulation, reactive power control, and restoration of operation after emergencies. Implementing energy storage systems into the power supply infrastructure will ensure stability, reliability, and efficiency of the system, enhance resilience, and promote the development of renewable energy sources [18].

Development of distributed generation. Reducing the “criticality” (meaning exceptionally high importance for the economy, industry, society functioning, and population safety) of energy generation facilities can be achieved through diversification of fuel supply sources and the development of renewable energy sources that do not rely on fossil fuels. The growth of distributed energy generation aims to decrease dependency on centralized electricity production and can enhance the resilience of the power supply system, especially in remote areas and when utilizing various energy sources. Over the past few years, there has been significant growth in distributed electricity generation, including the installation of household solar power systems for consumers in many regions of Ukraine [19]. These trends are primarily driven by economic factors but also offer considerable advantages in terms of resilience if these energy generation assets can operate independently of the voltage and frequency requirements of the centralized power system.

Secure communications. In modern power supply systems, communications are essential for their normal functioning. Previously, the design of power infrastructure aimed to minimize dependence on communications due to their high costs and low reliability. However, with the development of communication technologies, the dependency on them has significantly increased at all levels of power supply. For instance, electricity market systems, ancillary services, and others can negatively impact the system's reliability in case of communication failures. Implementing redundancy and reliable communication helps reduce dependency, but there is a risk in scenarios with limited communication infrastructure functionality, including cyber-attacks. Therefore, enhanced cybersecurity measures are necessary, and strategies for the operation of the power complex in the absence of communications should be developed.

6. Micro power systems (MicroGrid) with distributed renewable generation for enhancing the resilience of the power supply system

Increasing resilience requires the development of effective strategies for mitigating the impact and consequences of destructive events, as well as facilitating the rapid recovery of the power system. These requirements can be met through the integration of so-called local networks or micro power systems, also known as MicroGrids, which the International Electrotechnical Commission defines as “a set of controlled distributed generators and load resources located in close proximity to each other, consisting of several sources of alternating current, including at least one renewable energy source such as wind or solar” [20].

MicroGrid, essentially, is a small-scale electrical network designed to manage distributed energy resources and may include renewable energy sources (such as solar, wind, and/or hydro energy) along with conventional sources (such as diesel generators, gas turbines, etc.). These MicroGrids typically manage the energy load of multiple generation systems and incorporate certain energy storage systems. They are controlled using various types of software and management systems.

Among the aforementioned directions for strengthening the resilience of the power system, the development of MicroGrids with distributed renewable energy generation requires particular attention in modern conditions in Ukraine. According to another definition, MicroGrids represent intelligent power systems on a small scale, functioning as a single structure, integrating consumers and local distributed energy resources along with energy storage systems [21]. The definition of MicroGrids by the U.S. Department of Energy emphasizes that it is a group of interconnected loads and distributed energy resources that are confined within clearly defined electrical boundaries and operate as a single controlled entity in the power system [22]. According to data from Bloom Energy [23], around 500 new MicroGrids are already in the process of development or deployment, with the total capacity of such networks worldwide reaching several gigawatts.

The U.S. Department of Energy's MicroGrid development program [24] indicates that by 2050, distributed generation could constitute a significant portion of the generating capacity in the U.S., ranging from 30% to 50%. From 2016 to 2019, over 200 new MicroGrids were installed in the U.S., which is a 65% increase compared to the previous period (2013–2016). The average size of one MicroGrid is less than 5 MW. It is projected that the total global capacity of MicroGrids will increase from 3,500 MW in 2019 to 20,000 MW by 2028 [24].

The interest in distributed renewable generation within MicroGrids is driven by the decrease in costs and increased awareness and societal interest. According to forecasts from Navigant Research, commercial and industrial clients (C&I) are expected to significantly increase their investments in MicroGrids, growing from $200 million in 2020 to nearly $1.5 billion in 2029 [25].

Furthermore, one of the advantages of distributed renewable generation is the reduction in the use of fossil fuels. The share of MicroGrids relying on fossil fuels (such as diesel generators and mini-CHP) decreased from 89% in 2019 to 16% in 2021 [24], indicating the increasing environmental friendliness of such micropower systems.

These MicroGrids can be connected to the main power grid through a single point of connection or, in some cases, operate in an isolated mode, allowing them to function independently of the main energy infrastructure. Thus, islanding mode can be both permanent and temporary, forming dynamic energy islands in emergency situations that prevent the operation of the unified power system due to extensive damage or disruption to system-forming links. At the same time, they integrate both direct current and alternating current networks (due to the use of different energy sources) as well as battery energy systems and, potentially, fuel cells.

MicroGrids with renewable generation and energy storage systems have laid the foundation for smart grids, providing the ability to create a self-controlled power system that can reliably operate within defined electrical parameters through the organization of interconnections between distributed energy resources and controllable loads. The MicroGrid's control system (controller) performs several functions [26], including: (a) determining the time and method of connection and disconnection from the main grid; (b) ensuring the balance of active and reactive power when the MicroGrid is disconnected and operating in islanding mode, and (c) managing distributed energy resources (renewable generation and energy storage system) to support the load.

It should be noted that the integration of distributed generation sources into power systems is carried out at three hierarchical levels. Large-scale sources are usually connected through the point of interconnection to existing substations with voltage reduction or to specially built substations with voltage transformation at 110 kV and above for power transmission to major consumption centers. Medium-scale sources (up to several MW) are, in most cases, directly integrated into distribution networks at 6–35 kV. For connection to low-voltage networks, small-scale installations are used, which are applied by small consumers. Depending on the level of integration of distributed generation devices into electrical grids, the effective collaboration often requires the implementation of various new approaches, strategies, and technologies.

Microgrids, due to their ability to operate in both parallel and autonomous modes and switch from parallel to island mode, serve as an effective resilience resource for both transmission and distribution systems. Distributed energy resources, microturbines, wind turbines, photovoltaic modules, energy storage systems, etc., constitute critical units of local grids. Using microgrid technologies allows integration with the grid and multiple smart grid technologies, integrating distributed and renewable energy sources to reduce peak loads and provide power to critical energy-dependent facilities.

The design and construction of microgrids are influenced by various factors. Advancements in electricity production and distribution technologies allow the creation of systems that reduce energy consumption, utilize eco-friendly energy production methods, and meet critical requirements for power supply. During extreme events, distributed energy resources can provide consumers with electricity when the local grid operates in island mode or serve as a temporary resource (donor) for the power system. They can also facilitate faster service restoration after destructive events. The concept of local grids with distributed generation, storage, and energy control can reduce dependency on major transmission lines, lower network vulnerability, and improve its resilience and reduce restoration time.

Local grids with renewable generation (mainly solar and wind) can have a significant impact on improving the functioning of the power system during destructive events at the centralized energy generation or transmission level. Among the key factors influencing the resilience of the power system when employing local grids with distributed renewable generation are the following:

1. Autonomy: Local grids with renewable generation can operate autonomously, independent of centralized grids or transmission lines. This allows for providing electricity to remote or critical facilities, limiting the spread of outages, and preserving power stability in other areas.

2. Decentralization: Solar and wind generation enables creating energy sources directly within microgrids, avoiding dependence on large centralized power plants and reducing the load on centralized energy generation and transmission. This division of energy production and consumption among multiple small local sources helps improve load distribution and reduce the risk of system overload during emergencies.

3. Reduced reliance on fossil fuels: The use of solar and wind generation in microgrids reduces dependency on fossil fuels, which can be expensive and unreliable during emergencies.

4. Reduced carbon footprint: Utilizing renewable energy sources such as solar and wind reduces greenhouse gas emissions and other pollutants, contributing to environmental and public health improvements within the microgrid.

5. Flexibility: Solar and wind generators can be easily deployed and expanded in various locations within the microgrid based on needs and available resources. This allows for optimizing energy production based on variable conditions. Local grids with renewable generation can also be more flexible in load and energy management through smart grid technologies and control systems. Such grids can effectively respond to changes in production and consumption, ensuring stability during complex situations.

6. Reliability: Local grids can provide reliable power in case of issues with central grids or transmission lines. They can serve as backup power sources, reducing the risk of disconnection during emergencies.

7. Stability and recovery: Local grids can facilitate faster recovery after problems occur. This requires having reliable sources of renewable generation and efficient emergency response systems.

Fig. 3 illustrates how microgrids with distributed generation can be used to improve resilience during disruptions at different levels of the power supply system, as well as how the stability of an individual local network is strengthened [27].

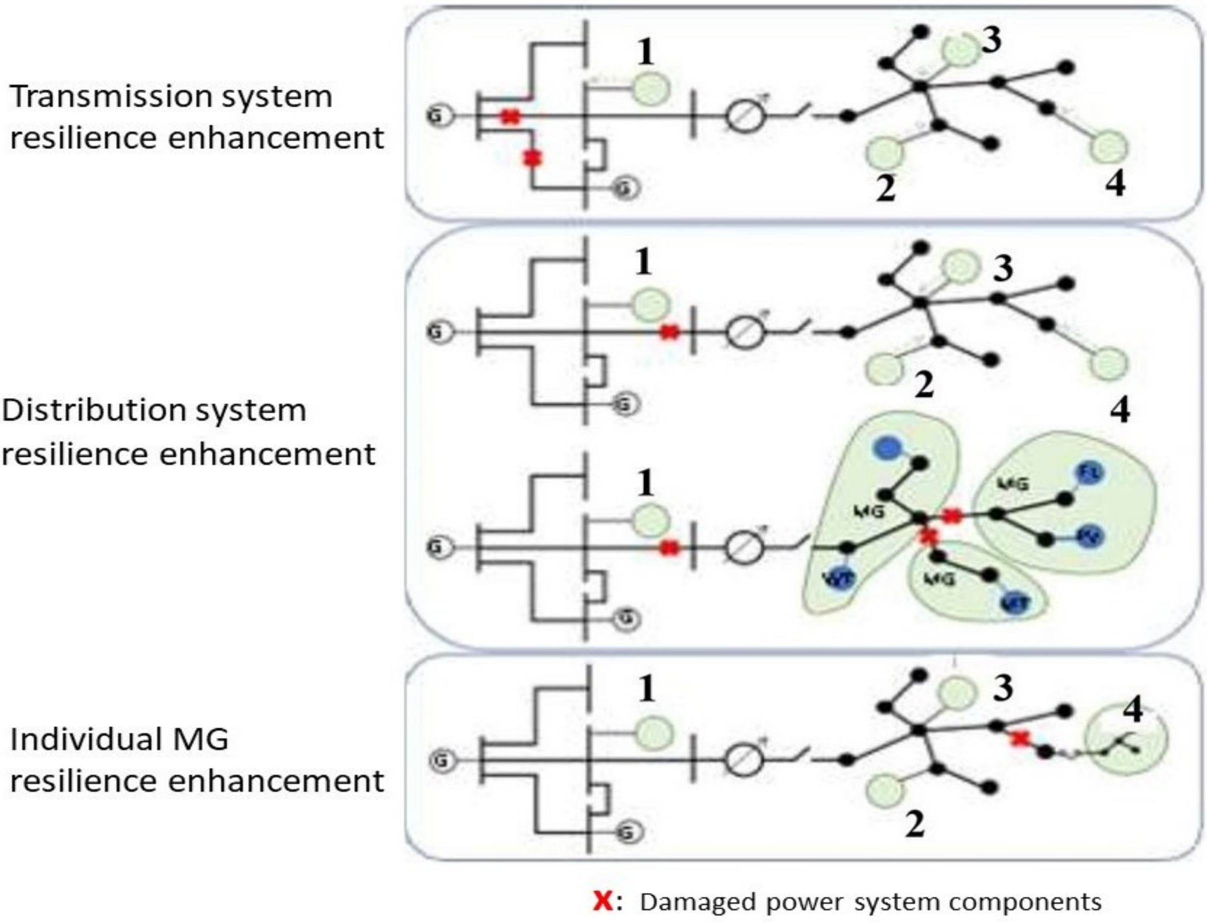

Fig. 3. Enhancing resilience during destructive events at various levels of power system [27]

Enhancing resilience at the transmission system level: In the event of line damages in the transmission system and isolation of a part of it, microgrids (MG) directly connected to the transmission system (MG1) or microgrids connected to the distribution system (MG 2–MG 4) can act as energy resources to meet the needs of the isolated part (both transmission and distribution systems) at the local level and reduce load gaps.

Enhancing resilience at the distribution system level: In the case of damages and isolation at the distribution system level, microgrids connected to it (MG 2–MG 4) can act as energy sources to meet the local needs of the distribution system. Additionally, in the event of multiple destructive events in the distribution system, it is possible to divide it into separate autonomous microgrids, using various sources of distributed generation to minimize load disconnection.

Enhancing resilience at the individual microgrid level: In the event of damages in the distribution system, leading to the isolation of a microgrid (MG 4), it can operate in an isolated (islanded) mode, properly allocating its resources to serve at least critical loads.

Creating and operating local microgrids with distributed renewable generation to enhance the resilience of the power system requires both investment and planning measures, as well as the implementation of advanced management and operational strategies. All types of actions must consider uncertainties arising mainly from the stochastic nature of renewable energy resources and potential damages in case of external threats.

Microgrids have significant advantages in enhancing the resilience of the power system by implementing various strategies, ranging from planning for emergency responses to ensuring reliable power supply to consumers. Ensuring the reliability of the power system occurs at different levels, starting from physically strengthening system components and operational restoration of services, and extending to the development of management strategies that reinforce power system resilience.

7. Approaches to assessing the impact of distributed renewable energy generation on the resilience of the power system

The relevance of assessing the resilience of the power system in the development of distributed renewable energy lies in the need to determine the nature and strength of the impact of these technologies on the overall stability and reliability of the power system. Distributed renewable energy generation brings changes to the traditional structure of electricity production and load distribution, which can affect the operation and stability of the system.

Currently, there are no standardized resilience metrics, and there is no universal metric that would be suitable for all cases. Most proposed quantitative assessments of resilience focus on monitoring system degradation and recovery, but do not consider its preventive and adaptive capabilities. Additionally, each category of assessment methods has its own advantages and limitations.

Analytical methods can reflect the impact of load levels on the resilience of the power system, but these metrics require significant computational costs and do not consider the time of degradation and recovery. Probabilistic methods are effective for assessing resilience as they can predict not only the severity of an event and its impact on the system but also the probability of its occurrence. However, when modeling the system, many assumptions need to be made, which can lead to significant errors due to overgeneralization and simplification. Resilience assessments based on reliability indicators use standardized indices that are well-developed and easily calculated. However, these indices do not account for catastrophic events caused by extreme destructive events.

To assess the resilience of the power system in the context of distributed renewable generation, various approaches and methods can be used, allowing for the consideration of different scenarios for the integration of distributed renewable generation and evaluating their impact on load, costs, reliability, and system stability [28]–[36].

In [28], limitations are considered to ensure an adequate operating reserve in the economic operation of microgrids and to support critical loads in case of failures in the main grid. The concept of smart distributed autonomous power supply systems is proposed in [29] to create a resilient microgrid, where

Demand Side Management methods are used as a tool to ensure critical load serving during emergency conditions. The study [30] develops a sequence of control decisions to be made for service restoration in systems consisting of multiple microgrids and subsequent islanding operation, and it is stated that this sequence of control decisions and actions allows for reducing load restoration time and improving system resilience. In [31], the development of load management functions in the microgrid is presented, including energy storage, electric vehicles, and consumer load control, which contributes to increased microgrid resilience after islanding for autonomous operation. In [32], a strategic planning approach is proposed to create resilient microgrids by optimally locating distributed generators in the distribution system to optimize the vulnerability, reliability, and economic efficiency of the microgrid.

Based on the reviewed literature, it can be concluded that resilience is a function of time and can be categorized into short-term and long-term resilience. Short-term resilience defines the attributes that a resilient power system should possess before, during, and after an event, namely, robustness/stability, resourcefulness/reserve capacity, and recovery. On the other hand, long-term resilience pertains to the attributes of an power system concerning new threats, changing conditions, and the system's ability to adapt to them.

In the work [33], an approach was proposed to assess the impact of the penetration level of renewable generation (ranging from 0% to 100%) and node voltage in the power system's resilience based on skew-normal distribution and complex network methods. The study focused on the impact of distributed generation on a power system with 2383 nodes (buses) in Poland. It was found that the initial fraction $F_0 \approx 1.6\%$ of loaded nodes goes beyond the nominal voltage. In this context, α represents the level of renewable energy production in local power systems.

Three scenarios were considered and analyzed:

1. $\alpha = 0$: Renewable generation production is approximately equal to the consumer load.
2. $\alpha = -1$: Renewable generation production exceeds the consumer load.
3. $\alpha = 1$: Renewable generation production is below the consumer load.

Further, depending on the *p*-share of renewable generation in the overall generation structure at the defined levels of renewable energy production α, the results are shown in Fig. 4.

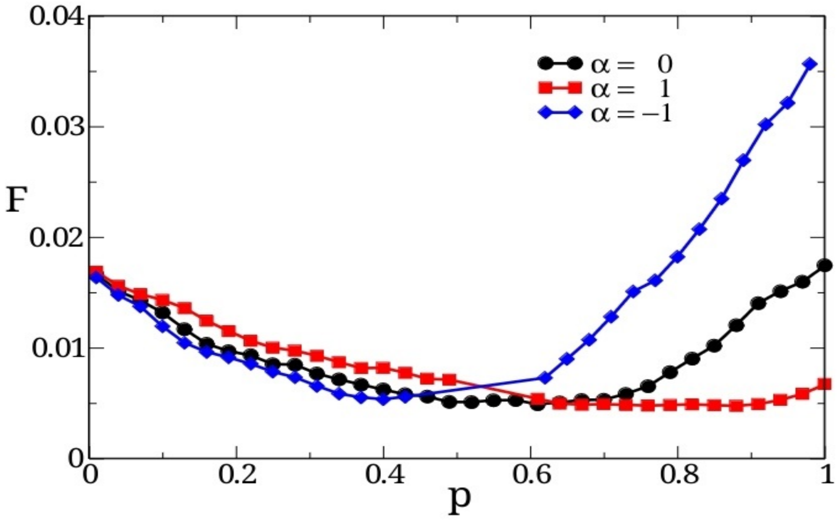

Fig. 4. The impact of distributed renewable generation penetration *p* on microgrid resilience at different α values [33]

It should be noted that lower *F* values of the relative share of nodes operating close to the nominal voltage, correspond to higher resilience. As evident from the research results, the expansion of distributed renewable energy generation initially enhances the resilience of the power system. However, at higher *p* values ($p \geq 0.6$), the resilience deteriorates, particularly if the distributed generation on average supplies more energy than the normal load requirements ($\alpha = -1$). Therefore, it is recommended to maintain the levels of renewable energy generation below the load requirements ($\alpha = 1$). Consequently, it has been identified that uncontrolled deployment and growth of renewable energy generation can overload the power system beyond its design parameters.

During assessing the resilience of power system with distributed renewable generation, it is important to consider various factors and complex interconnections within microgrids. The generation structure, type of renewable energy sources, storage technology, and their techno-economic parameters can significantly influence the functioning of each individual microgrid and its contribution to enhancing the resilience of the country's power supply system. Some proposed methods [34]–[36] may not accurately estimate the real properties of the microgrid itself. Existing approaches are suitable for visualizing and measuring specific aspects (e.g., system control efficiency [34] or economic aspects [35] or from the point of view of management theory [36]) of operational and infrastructure resilience of the power system but have some limitations and do not consider the following crucial factors:

1. Self-sufficiency: Increasing the penetration of distributed renewable generation can enhance resilience if the system has the capability for full autonomous operation when disconnected from centralized grids or remains self-sufficient while maintaining connections to the centralized grid. Autonomous and/or self-sufficient microgrids can be more resilient to external disruptive events.
2. Coherence (preserving all key connections within microgrids): Considering the connections and interactions among distributed generators, energy storage systems, and consumers within microgrids is crucial for assessing resilience. Systems with balanced interactions between participants can be more robust to failures.
3. Microgrid flexibility: Distributed renewable sources can provide stability, but their effectiveness may depend on the system's flexibility in load management and production balance.
4. Microgrid response: In the case of significant failures or emergencies, the resilience of the power system may also depend on the speed and effectiveness of the response within the microgrid with distributed renewable generation to such events.

Formalizing and considering these factors will help achieve a more comprehensive assessment of the resilience of the power system and develop effective strategies to enhance its stability and reliability. Additionally, the application of mathematical modeling, economic analysis, and other analytical methods can aid in determining optimal strategies for the implementation of distributed renewable generation while considering the improvement of power system resilience. Currently, microgrids are extensively studied and deployed, but further research is necessary to explore reliable management architectures for microgrids with distributed renewable generation. Methods for forecasting with consideration of intermittency and variability of solar and wind generation should be developed. Furthermore, optimization of integration and synchronization between microgrids and centralized power systems is essential to achieve mutual coordination for their sustainable and reliable operation.

8. Conclusions

The power sector is an integral part of critical infrastructure, serving as the epicenter and driving force of the economy, national security, and environmental situation in a country. It is interconnected with other critical infrastructure components, such as gas and water supply, transportation, and communication systems. Any disruption in the energy supply system directly and significantly impacts the functioning of these critical infrastructure components. Therefore, enhancing the power system resilience is crucial to ensure the continuous operation of the overall critical infrastructure.

The definitions and key characteristics of the power system resilience in modern scientific literature are considered. Resilience of a power system can be divided into two main categories: 1) infrastructure resilience and 2) operational resilience. Infrastructure resilience is primarily defined as the physical strength of the power system, which is sufficient to withstand and be less susceptible to damage from major disruptions. Operational resilience relates to the continuity of operations, ensuring uninterrupted supply or sufficient available generating capacity, despite adverse events or disruptions.

It has been identified that the most necessary and promising approaches to enhance the power system resilience include the development of relevant regulatory framework, physical protection systems (e.g. shelters of different kinds) for energy infrastructure objects, the utilization of automatic frequency and power regulation systems, ensuring resource adequacy (including technical component reserves), promoting the development of distributed generation, integrating energy storage systems into the electric grid, and strengthening cybersecurity. Implementing these approaches will enable the energy complex to increase its self-recovery capability and resilience in destructive extreme situations that go beyond typical failures.

In this research, the role of micro power systems (MicroGrid) with renewable energy sources in enhancing the power system resilience was analyzed. Additionally, the functions of microgrids that contribute to improving the stability of power systems were summarized, such as service restoration, network formation strategies, control and stability, as well as preventive measures. It was found that local microgrids have significant potential to increase the power system resilience by implementing various strategies, ranging from planning for emergency situations to ensuring reliable energy supply to consumers for rapid response to military, environmental, and anthropogenic crises. The concept of local networks with distributed generation, storage, and energy control can reduce dependence on main power transmission lines, decrease network vulnerability, and simultaneously improve its resilience and reduce recovery time.

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ПОКРАЩЕННЯ РЕЗИЛЬЄНТНОСТІ ЕНЕРГОСИСТЕМИ ШЛЯХОМ ЗАСТОСУВАННЯ МІКРОЕНЕРГЕТИЧНИХ СИСТЕМ (MICROGRID) З ВІДНОВЛЮВАНОЮ РОЗПОДІЛЕНОЮ ГЕНЕРАЦІЄЮ

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Анотація. *Енергетичний сектор відіграє критичну роль у функціонуванні економіки та безпеки країни, знаходячись у тісному зв’язку з іншими важливими інфраструктурами, включаючи газопостачання, водопостачання, транспорт та телекомунікації. Підтримка стабільного електропостачання є вирішальною для безперебійної роботи цих систем. Інтеграція локальних мереж з розподіленою генерацією з відновлюваних джерел енергії (ВДЕ-генерацією) у загальну енергосистему є одним зі способів підвищення її резильєнтності. Гнучкість, стійкість, керованість та здатність до самовідновлення мікромереж роблять їх ефективним рішенням для покращення стійкості енергосистеми. Електромережа чутлива до збурень та руйнувань, що можуть викликати масштабні відключення споживачів електроенергії. Статистичні дані вказують, що приблизно 90% відключень відбуваються через проблеми в системі розподілу, тому особливий фокус у дослідженнях направлений на локальні мережі з розподіленою ВДЕ-генерацією. В ході дослідження була проаналізована роль мікромереж з ВДЕ-генерацією у підвищенні резильєнтності енергетичних систем. Крім того, узагальнено функції мікромереж, які сприяють підвищенню стійкості енергетичних систем, такі як відновлення обслуговування, стратегії формування мережі, контроль і стабільність, а також запобіжні заходи. Виявлено, що локальні мікромережі володіють значним потенціалом підвищення резильєнтності енергосистеми шляхом реалізації різноманітних стратегій, від планування реагування на надзвичайні ситуації до забезпечення надійного енергопостачання споживачів для швидкого реагування на військові, екологічні та антропогенні кризи. Концепція локальних мереж з розподіленим виробництвом, зберіганням та контролем енергії може зменшити залежність від магістральних ліній енергопередачі, знизити вразливість мережі і водночас покращити її стійкість та зменшити час відновлення.*

Ключові слова: резильєнтність, локальні енергетичні системи, MicroGrid, розподілена генерація, відновлювані джерела енергії.

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