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Review article

Digital platform of reliability management systems for operation of microgrids

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A R T I C L E I N F O

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A B S T R A C T

This paper deals with the issue of ensuring the reliability of microsystems in the modern-day development of digital control technologies. The use of digital technologies to manage the reliability of microsystems stems from the development of various modern energy technologies with complex structures that require enhanced management systems to ensure their reliability. In this paper, we propose the use of digital platforms to manage the reliability of microsystems. The way digital platforms function makes it possible to automate the process of collecting, processing, and storing the necessary information about both power equipment and the operating modes of distribution networks and, in so doing, to assess and ensure the reliability of microsystems at all stages of the life cycle. In this paper, we present the main operational characteristics and principles of digital platforms. To analyze the reliability of microsystems within the framework of the functioning of digital platforms, we propose the use of machine learning methods. We suggest two algorithms for assessing the reliability of microsystems. In the first algorithm, the model is trained to analyze the regime indicators of the microsystem and, on the basis of these, to determine the reliability indicators. In the second algorithm, the model is trained to immediately determine the reliability indicators of the microsystem. Practical results have shown the effectiveness of the proposed algorithms in terms of the speed of assessing the reliability of microsystems while maintaining the required accuracy of calculations.

Contents

1. Prerequisites for developing digital platforms to manage the reliability of microgrids

Ensuring a reliable power supply to end users depends on several factors. From the engineering perspective, the supply of electricity to end users is carried out through a chain of technological links: to electricity generation, to electricity transmission, and to electricity distribution. The first two links form the basic structure of the electric power system (EPS). Distribution networks are powered mainly from the step-down substations of the main structure of the EPS. In terms of reliability, all technological links are connected in series, and each has a complex structure with different types of connections inside it. As evidenced in actual practices of power system operation, the power distribution link (i.e., distribution networks) has the lowest reliability.

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Distribution networks account for about 70% of the total number of power outages at the end users. It should be noted that the share of distribution networks in the total length of the power grid is more than 90% (this value may vary from country to country); note, too, that distribution networks, due to their design features, are the most exposed to various types of threat. One can highlight several key reasons for the low reliability of distribution networks and its responsibility for an increased failure rate of electrical equipment, for example: high wear and tear on electrical equipment; the high load of existing distribution networks, well beyond the design values (most frequently observed in urban agglomerations); and the low level of observability (Antares, 2022).

As well as issues related to ensuring the reliability of distribution networks, it is worth noting some current trends in the development of various energy technologies that are integrated into distribution networks and affect their reliability. First, attention should be focused on the unified vision for the development of the modern electric power industry, including distribution networks, on the basis of which several important directions are being formed. We focus here on the main ones:

The AM include the following elements:

- increasingly active behavior on the part of power consumers. The consumer turns from a passive element of the system into an active one. Whereas consumers formerly only took off power and electricity in certain amounts, today's consumers, if sufficient incentives are created, can respond to signals from the power system to reduce load and implement various tools to manage their power consumption. The establishment of consumer load management mechanisms is a positive phenomenon from the perspective of ensuring the reliability of distribution networks, making it possible to smooth out consumption peaks during periods of maximum risk of power supply disruption;
- integration of distributed generation, including renewable energy sources (RES). This direction is a characteristic feature of the modern electric power industry. The main sources of motivation driving such transformations are the high cost of electricity from the centralized power system, difficulties with, or the impossibility of, technological coupling, and in some cases low reliability of power supply. Although in terms of ensuring the balance of power, integration of distributed generation is a positive move, in some cases sustainability issues may arise (Filippov et al., 2019; Kulikov et al., 2020; Urpelainen, 2018);
- integration of energy storage systems (ESS). Various energy storage technologies are currently being rapidly developed in power systems at all hierarchical levels. Energy storage facilities of different energy volumes can be connected at different places in the distribution networks, including directly to electricity consumers. The main obstacle to the introduction of ESSs is their high cost. In terms of ensuring the reliability of power supply when integrating ESSs, we can conclude that they are, essentially, an additional backup source of power and energy and increase the reliability of distribution networks.

The integration of the technologies presented above forms a renewed and more complex distribution network structure, where multi-directional power flows and additional challenges to power supply reliability arise. This new structure of distribution networks is essentially a microsystem. Fig. 1 shows schematically the existing and prospective structures of distribution networks (Buchholz and Styczynski, 2020).

Today's electricity consumers are becoming increasingly demanding regarding the reliability of power supply. If we analyze recent system accidents in power systems, we note that the economic and environmental consequences of these, as well as the damage they cause to people's health and lives, are becoming increasingly significant (KWTX.-T.V. News 10, 2021). This happens for several reasons:

- increasing the dependence of critical loads on the reliability of the power supply. Requirements for modern critical systems, such as heating, water supply, fire-fighting, and security, are at a high level. This is primarily due to the facilities being serviced, which are often crowded places, while the failure of critical loads, including those due to the failure to supply electricity, have consequences that threaten people's lives and health. Another reason may also be the harsh operating conditions of critical loads, where the cost of failure of such a load increases significantly due to further adverse events on the consumer side;
- the high cost and high sensitivity of modern electrical loads. Modern household consumers of electricity have expensive electrical appliances, which are extremely sensitive not only to power failures but also to fluctuations in the parameters of operating conditions.

As electricity is a universal commodity used in almost all areas of human activity and also in critical services, the degree of importance of reliable power supply for many such areas increases as harsh climatic conditions intensify. The importance of the process of ensuring the reliability of the electricity supply is relevant both in cold climates and in hot ones, but it is worth noting that in the event of a power outage for consumers in an environment with a hot climate, the consequences may be much milder than for those in a cold one. In practice, a thorough analysis of the operating conditions of consumers must be conducted and their requirements for reliability precisely determined. There are several classifications of consumers, the most common being division by type. Consumers include urban, industrial, and rural consumers, railroads, and gas and oil pipelines. Ensuring the reliability of electricity supply for each type of consumer has its own specific aspects. In addition to the division of consumers by type, there are division by reliability: for example, in Russia, there are three categories of reliability for electricity consumers. For each category, outage times and redundancy levels are defined. Whereas previously the requirements for ensuring the reliability of electricity supply for each category were strictly defined, today they have been relaxed and are now subject to contractual relations (i.e., the consumer negotiates the level of reliability of power supply with the power supply company and pays for such a level). An alternative option is to install one's own energy sources. As well as power outages, situations in which the power supply fails to meet quality standards are also becoming critical for today's consumers and are leading to expensive equipment failure and the disruption of technological processes.

The issues of managing microgrids and ensuring their reliability during a pandemic, as well as during other such emergencies, merit a special mention. The multiple effects of the pandemic have led to several significant economic issues. In particular, we can identify the following issues affecting the reliability of microgrids: an increase in the risk of illness of the personnel of microgrid companies; a decrease in the solvency of consumers; disruption of the normal technological process due to epidemic restrictions; and a slowing down of the expansion process (Department of International and Regional Cooperation of the Accounts Chamber of the Russian Federation, 2020).

As far as microgrid operations that operate today are concerned, systems need to be created to monitor and forecast the parameters of power equipment and analyze operating conditions so as to maximize the level of reliability of power supply

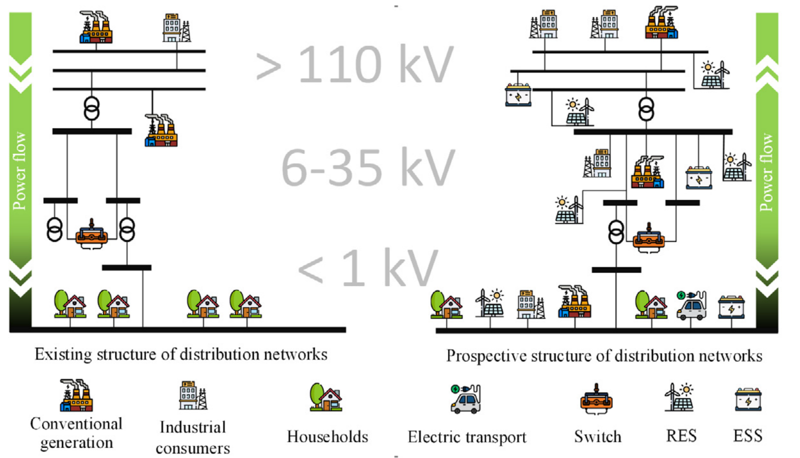

Fig. 1. The technological transformation of distribution networks to microgrids.

to consumers. This can be done by integrating solutions based on the digitalization of control processes into microgrid reliability management practices.

This paper aims to lay the groundwork for a new automated system that manages the reliability of power distribution systems and microgrids built on the foundation provided by distribution systems. The main goal of a new automated system is to maximize the efficiency of its operation to ensure the reliability of power supply for all possible resources at the lowest possible cost. It should be noted that the implementation of the proposed new reliability assurance system will maximize the effect of the involvement of all stakeholders in the process of ensuring the reliability of the power supply. This study stands apart from other similar research in the field in that it provides a comprehensive analysis of possible ways of ensuring the reliability of microgrids.

2. Ensuring the reliability of power supply: Benefits for all electric power industry entities

The task of ensuring reliability is one of the priority areas in the activities of all entities of the electric power industry. Ensuring reliability in the case of power supply has two well-defined components. The first is the economic damage that occurs when power equipment fails and consumers are then disconnected. Moreover, the damage is a complex nonlinear function that depends on many factors, such as the type of consumer, the time of power outage at the consumer end, and the climatic conditions in which the power equipment is operated (Krupenev and Perzhabinsky, 2017; Billinton and Li, 1994). In addition to direct damage, which is straightforward enough to assess in some cases, there is also indirect damage, the assessment of which is a somewhat more difficult task. For electricity consumers, the damage depends primarily on the initial moment of the power outage, the duration of the outage, and several external conditions. For a power utility, damages can be based on an estimate of the cost of damaged equipment and lost profits. The latter is essentially related to the investment expended on improving the facility's level of reliability. These costs, first, must be rationally allocated to the top priority technical and organizational measures, and, second, kept to a minimum to ensure the necessary level of reliability. The graphical interpretation of these components is presented in Fig. 2.

As can be seen from Fig. 2, there is an optimal level of reliability of power supply that should be sought in the management of the operation and the management of the expansion planning of distribution networks.

3. The notion and basic principles of the digital platform for managing the reliability of microgrids

To manage and maximize the level of power supply reliability in today's environment, specialized tools need to be created that will make use of all the possibilities and advantages of digital technology. Such solutions can be organized based on digital platforms. A digital platform refers to a software multi-agent space where users (agents) can communicate and interact with each other and gain (temporary or permanent) access to products, services, or resources provided by other users to reduce the costs when implementing various processes. The use of such technologies is already undergoing development in the energy industry to address various issues. Studies Duch-Brown and Rossetti (2020), Kloppenburg and Boekelo (2019) present an overview of solutions of this kind used in the power industry. There are several types of such digital platforms, grouped based on various problem areas addressed:

- - market-based. Most of these digital platforms are designed to organize retail electricity markets. Several platforms of this kind are already functioning: Powerpeers (2022), Vandebron (2022), Piclo (2022), etc.;
- engineering-based. These platforms are mainly designed to organize the centralized management of power and electricity consumption. The following platforms of this kind have already been developed and adopted: SonnenCommunity (2022), EnecoCrowdNett (2022), Cityzen vpp (2022), and others;
- investment-based. These platforms are designed to facilitate the attraction of investment in the construction of energy facilities. The following platforms are already in operation: ZonnepanelenDelen (2022), SunShare (2022), etc.

In Russia, the idea of creating digital platforms to solve various problems in the energy sector is also gaining momentum. Study Kovalyov and Nebera (2020) presents the methodological foundations of a digital platform for solving several problems in the field of intelligent management of distributed energy resources.

If we focus on the task of managing the reliability of microgrids, we can formulate the goal of the digital platform operation as that of obliging all entities operating within microgrids to become involved in activities that ensure the reliability of both microgrids and power supply, while deriving the maximum benefit for all entities involved. Based on that goal, the digital platform for managing the reliability of microgrids is a software

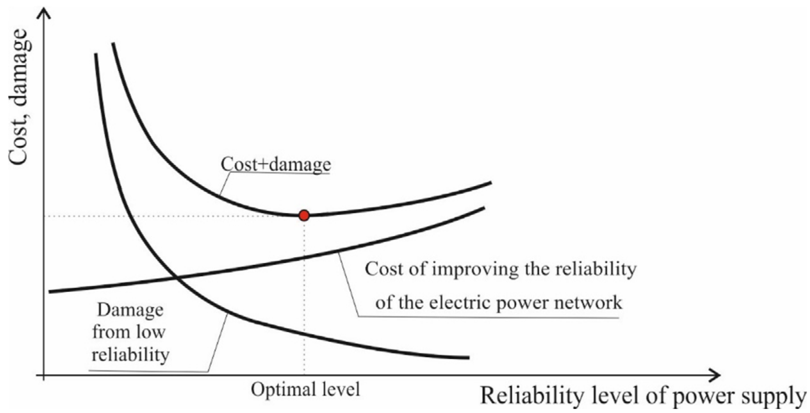

Fig. 2. Graphical interpretation of determining the optimal level of reliability of power supply to consumers.

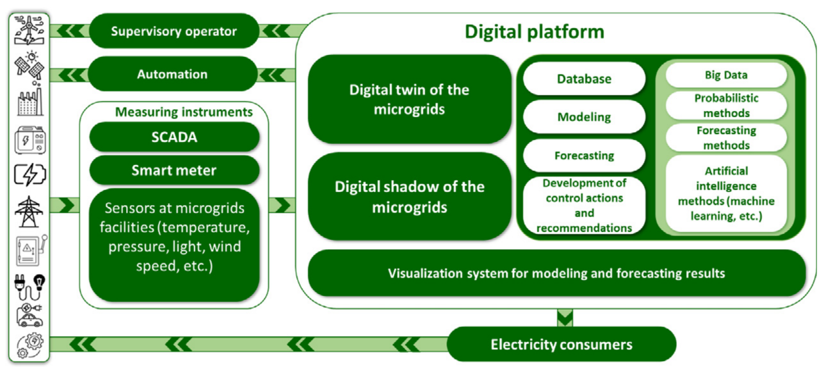

Fig. 3. Aggregated structure of a digital platform for managing the reliability of microgrids.

multi-agent space in which agents (electric utilities, maintenance companies, generators, consumers, etc.) can interact in a mutually beneficial way to maximize the level of microgrid reliability and maintain the reliability of power supply to consumers at the maximum or required level. The aggregated structure of such a digital platform and its interaction with the entities and facilities of microgrids is shown in Fig. 3.

The arrows in Fig. 3 indicate the flow of information. It is worth noting that as such digital platforms are based on infrastructure, system modeling (in this case microgrid modeling) is a prerequisite for effectively ensuring the reliability of this infrastructure. Adequate modeling can be carried out only by the organization that directly manages the networks in question.

The principle of the digital platform operation is as follows: information from the measuring systems and instruments on the elements of microgrids is transmitted online to the servers of the digital platform, where it is processed and accumulated. From the incoming information, an up-to-date model of the microgrid is created, as well as a forecast of the necessary information for the future. Depending on the work planning task being solved, the time horizon can be operational (up to 1 h), short-term (up to 1 day), medium-term (up to 1 month), and long-term (up to 1 year). The digital platform should also be used to solve the problems of designing the expansion planning of microgrids.

The digital platform consists of two main modules: the digital twin (Attaran and Celik, 2023; Bai and Wang, 2022) and the digital shadow (Santolamazza et al., 2020; Riesener et al., 2019).

The digital twin of microgrids is a virtual copy that most accurately captures the parameters and progress of processes occurring at physical facilities. The digital twin, created when the required amounts of data are received from the physical facilities, forms the necessary commands for control actions at the physical facility. The basis of the digital twin is a mathematical model of the microgrids that takes into account as accurately as possible all the features of the modeled facility and its elements; this allows the formalization of the formation of tasks to be solved within the framework of its reliability management. For example, when analyzing emergency operating conditions (reliability), power shortages need to be determined, and when analyzing normal operating conditions the values of various economic performance metrics also need to be ascertained.

The digital shadow of microgrids is understood as a processed array of information about the operation of a facility, which reflects direct and feedback links, about the influence of various internal parameters of the facility and external actions on its behavior, under various operating conditions. As part of the creation of the digital shadow of the facility, an important point when collecting, processing, and accumulating further information in specialized databases is to collect only truly necessary information and subject it to "deep" filtering to optimize its amount and usefulness.

Digital twins and digital shadows are based on specialized computational tools. These tools are designed: (i) to perform the entire cycle of operations for collecting, storing, and processing network operation data; and (ii) to generate the necessary control actions to maximize the reliability of electric power networks under emerging operating conditions. Note that along with the use of rigorous mathematical methods to solve the problems stated above, artificial intelligence methods are now being used. These methods allow an approach to be found to problems that were difficult to solve by rigorous methods for various reasons (for example, because of the dimensionality of the problems). At the same time, methods of artificial intelligence provide an unprovable solution, and should therefore be subjected to additional checks, as the cost of error in the power industry management, especially an operational error, can be very significant and exacerbate the technological problem being solved.

The basis for managing the reliability of microgrids is the reliability assessment. The reliability assessment of microgrids should be carried out by specialized methods using special-purpose software products. Based on the obtained values of reliability metrics, control actions are developed to maximize their level. In this way, feedback to control objects and energy consumers is formed. This feedback can be of three kinds:

1 Supervised control. This is a traditional way of exercising control over the power grid. In this case, we assume its automation to be in the form of creating a system of remote control of switching facilities. In the case under consideration, we assume its automation to be in the form of creating a remote control system for switching objects.
2 Direct management of power grid facilities. It is assumed that the process of managing the reliability of microgrids, especially their operational control, requires some of the control commands to be automated to ensure the maximum level of reliability This means transferring commands to the switching facilities of the microgrids based on the reliability assessments obtained in the computing unit of the digital platform. In the same way, it is also possible to form a local automatic load-shedding system, which is an analog of special automatic load-shedding. To achieve this, the amount of load to be disconnected needs to be produced in advance and potentially mutually beneficial contracts with power consumers entered into. If the actual threshold is expected to be reached or reached, which characterizes the extent of an accident, the required load must be shed automatically.
3 Management through electricity consumers. Increasingly active behavior on the part of power consumers, especially in the process of operational management, can be an effective tool for managing the reliability of microgrids. This calls for user-friendly tools, adapted to user needs, that visualize the current microgrid reliability situation. Such tools can be implemented in the form of a mobile or desktop application that will signal the risk of disconnection of a particular consumer. In the event of a "tense" situation in the microgrids, such as the overloading of some elements, consumers should be notified so they can balance their electricity needs. This means that the consumer can choose either to reduce the power they are consuming, unload the power grid, and reduce the risk of its emergency shutdown with all the ensuing negative consequences, or to not reduce the power they are consuming, which would increase the risk of accidents in the microgrid and cause economic damage to consumers. If the consumer has the ability not only to reduce their power consumption but also to generate or deliver stored power, and the microgrid allows this, then signals from the digital platform should be an incentive for such actions as well. An application of this kind does not just presuppose the ability to directly change the mode of consumption but also serves only to transmit information about the state of the system, due to vulnerability to cyber threats.

In this way, the digital platform can participate in all phases of microgrid reliability management, helping to address several important issues.

The main operational management tasks to be solved will be:

- forecasting the parameters of the power equipment that affect its reliability;
- assessing the reliability of the current microgrid operating conditions (with results displayed on the digital panel);
- automatic reconfiguration of the microgrid in pre-emergency and emergency conditions;
- automatic adjustment of power system protection (recalculation of setpoints) for the current network configuration;
- making recommendations to the supervisory authority regarding control measures.

The main tasks of short-term planning (up to 1 day) will be:

- forecasting of parameters of power equipment affecting its reliability;
- assessing the reliability of the microgrid for the day ahead;
- adjusting repair plans for power equipment;
- making recommendations to the supervisory authority on control actions.

The main tasks of medium-term planning (up to 1 month) will be:

- forecasting the parameters of power equipment affecting its reliability;
- assessing the microgrid reliability for the month ahead (displaying the result on the digital panel);
- adjustment of repair plans for power equipment;
- making recommendations to electricity consumers on electricity consumption (storage, generation).

The main tasks of medium-term planning (up to 1 year) will be:

- forecasting of parameters of power equipment affecting its reliability;
- assessment of the microgrid reliability for 1 year ahead (with results displayed on the digital panel);
- adjustment of repair plans for power equipment;
- recommendations on eliminating bottlenecks in the microgrid, and development of expansion plans.

4. Basic principles of organizing digital platforms for managing the reliability of microgrids

The integration of digital platforms for managing the reliability of energy infrastructures, including power distribution systems, is a complex process that involves the interaction of many stakeholders in the energy sector. It must be stated clearly that the integration of such solutions should pursue a reasonable goal. In this particular case, the main goal is to ensure the reliability of the power supply. At the same time, the solutions to be implemented must be economically feasible. Apart from the positive effects of the implementation of digital platforms, there is also a risk of a negative impact on the reliability of the performance of the power supply. This may be due to a lack of elaboration of the principles underlying the operation of the platforms and failure to consider the factors affecting the reliability of the digital platforms themselves. The creation and operation of digital platforms need to be based on certain principles, the main ones being:

1 Adaptability. Quick adjustment of the digital platform to changes and new technologies without compromising the integrity of the system, plus working with open standards. Power systems are evolving and energy technologies are developing at a fast pace as new facets of their operation emerge. This affects the global control systems of the entire array of such equipment. Management systems in general and reliability systems in this particular case must thus be capable of embracing the new specifics of power equipment. An important aspect of the operation of microgrids is the model of relationships among the entities involved

(companies and consumers). The relationship model is constantly evolving, with new relationship mechanisms emerging. The digital platform should provide for such mechanisms. Another essential component of the relationship between suppliers of reliable power supply and consumers is the emergence of new services, which must also be taken into account.

2 Continuity. When organizing the work of a digital platform, it is necessary to establish a process of continuous collection and processing of information, an assessment of the required reliability metrics, and the development of a set of control actions and recommendations. The functionality that a digital platform is endowed with lies at its core. Therefore, for the efficient operation of such systems, it is necessary to continuously collect and process the actual parameters of microgrids and perform subsequent tasks based on these. All of the above processes, such as data collection, reliability assessment, and generation of control actions, are resource-intensive and necessitate the development of computationally efficient techniques and software tools for (i) reliable reproduction of the underlying technological processes and (ii) ensuring the necessary performance of such calculations. Naturally, such solutions are only possible with the use of state-of-the-art methods and technologies, such as cloud computing, Big Data, and artificial intelligence methods.

3 Parallelism. The processes of collecting, analyzing, processing, and calculating must be carried out simultaneously. As part of digital platform operation, many processes are performed simultaneously to collect and process raw data, assess and optimize microgrid reliability, interact with stakeholders, and control power equipment. To perform many of the above processes, special options must be provided in the practical implementation of digital platforms.

4 Security. Protection against external and internal actions. Maximum protection needs to be provided against interference in the management of the digital platform. Cybersecurity issues are extremely important in applications involving global data transmission systems. One of the purposes of the digital platforms investigated in this study is to control microgrids during periods that are deemed critical from the standpoint of power supply reliability. During such periods, given that any disruption of the reliability of the digital platform's functions can greatly exacerbate the problem of power supply reliability, the requirements to protect the digital platform from external and internal influences must be stringent.

5 Customer-centricity. Accessible and understandable services and equal opportunities must be provided for consumers to connect to the digital platform. Consumers are agents of interactions that take place in microgrids. Integration of digital platforms into microgrids triggers their activities. First, consumers have an incentive to reduce the load during periods of high system load and during periods when there is risk of major accidents. Thus, it is mandatory to establish services that inform consumers early on, both clearly and concisely. Second, it is possible to sign contracts with consumers in advance, which stipulate limits on the supply of power to consumers during periods that are considered risky in terms of ensuring the reliability of the system and its loads.

5. Assessment of system reliability for microgrids using machine learning methods

One of the most important objectives in the reliability control system for microgrids based on digital platforms is to assess various types of system reliability. Moreover, the assessment methods should be computationally efficient (i.e., capable of assessing reliability as quickly as possible while maintaining the required accuracy), as some of the important problems that can subsequently arise are solved based on the obtained reliability indices. To solve the problem of assessing system reliability, two algorithms were developed using machine learning methods. The algorithms developed are universal and can be applied to assess any kind of system reliability. The algorithms are based on the Monte Carlo method, which is the most appropriate for analyzing the reliability of complex systems (Billinton and Li, 1994; Krupenev et al., 2020; Kovalev and Lebedeva, 2019).

When using algorithms based on the Monte Carlo method, the reliability assessment accuracy is determined by the formula:

$$\Delta = \sqrt{\frac{D\zeta}{N}}$$

where ζ is a random variable simulated by the Monte Carlo method, $D\zeta$ is the variance of the random variable ζ, N is the number of trials. The formula shows that the accuracy of the result has quadratic dependence on the number of states and their heterogeneity. In the algorithm presented below, it is proposed, without changing the number of states (or slightly increasing it), to change the method of obtaining the implementation of a random variable to a faster one using machine learning methods. At the same time, the preservation of accuracy is achieved due to the quality of forecasting by machine learning methods, in other words, due to the preservation of the original variance. The very value of the required accuracy of calculations is determined based on the specifics of the problem solved using this platform.

The requirement for accuracy and speed of reliability assessment stimulate the application of increasingly effective mathematical methods. At the same time, machine learning methods are being used increasingly widely in different fields. Researchers and engineers are primarily attracted by the breadth of their application within Big Data. Machine learning is applicable in almost every area of our lives. The number of publications on the subject of artificial intelligence is growing every year, as is the breadth of the areas covered (Shoham et al., 2018).

For many of the problems arising where machine learning is applied, the use of the supervised machine learning problem statement is proposed. Using this approach, a finite set of precedents is formed, and each precedent is presented as an "object (data about the applicant, feature description)–response pair. " This set is called the training set. Based on this set, we need to identify the general dependencies that are inherent, not only in this sample but also in the process described as a whole, and to build an algorithm that takes a description of the object as input and produces an answer at the output.

Supervised learning is a structural object. The main types of supervised learning problems that can be used to assess system reliability are the classification problem, the regression problem, and the multitask regression (Krupenev et al., 2020). For the problem of assessing the system reliability of microsystems, the best characteristics can be obtained using multitask regression.

Multi-objective (multitask) regression (Breiman and Friedman, 1997) is a problem statement from the field of multitask learning. It aims for the simultaneous prediction of several continuous target variables based on the same set of input variables (features). A set of related or similar learning problems is solved simultaneously, using different learning algorithms that have a similar internal representation. As a rule, as methods for solving such problems, ordinary regression functions are used, built in an amount corresponding to the number of answers.

At the base of each described problem statement, various machine learning methods can be used, which are characterized

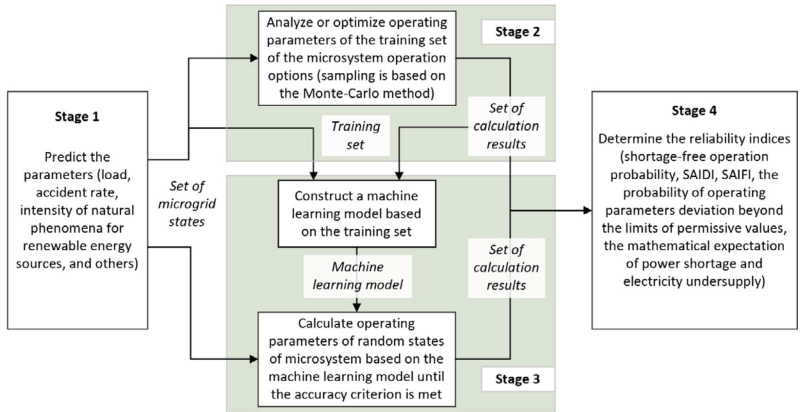

Fig. 4. Algorithm for assessing system reliability based on analysis of operating parameters of calculated states using machine learning methods.

by different properties. At the same time, it cannot be said that the effectiveness of one method is always higher than another. It must always be considered as relative to the problem being solved; it is impossible to assess the applicability of a particular method in theory without conducting an experiment using it. It is also important to note that the very concept of efficiency will depend on the goals set for the machine learning algorithm. For some tasks, the training time will be critical; for others, the accuracy of the forecast; for others, independence from the quality of the training sample or a combination of various factors. The variety of machine learning methods is great. In the research we used methods based on supervised learning, namely: linear methods, K-nearest neighbors, Bayesian methods, support vector machine, random forest, gradient boosting, etc. And it is worth noting right away that in the example considered, the most computationally efficient turned out to be gradient-boosting.

Fig. 4 shows an enlarged structure of the first algorithm, in which machine learning methods are used to determine the operating parameters of the system in the generated random states of the power system.

As seen in Fig. 4, the first stage involves projecting the microgrid parameters, including loads, accident rate, intensity of natural phenomena for renewable energy sources, and other random variables used in assessing the reliability of the system. Then, at the second stage, a training sample is built using the Monte Carlo method to form a set of randomly calculated microgrid states; next, the operating conditions of the generated options are analyzed or optimized. Additionally, at this stage, the archival microgrid variants (if there are any) for the previous period are processed and included in the training sample. Then, at the third stage, a machine learning model is constructed based on the training sample, and the operating conditions of random states of microgrids are calculated based on the machine learning model. The fourth and final stage determines the reliability indices of microgrids for the prediction period, such as the shortage-free operation probability, System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), the probability of operating parameters deviating beyond the limits of permissible values, the mathematical expectation of power shortage and electricity undersupply, and other indices.

Fig. 5 shows an enlarged structure of the algorithm, in which machine learning methods are used to determine the reliability indices of the system.

The first part of the algorithm presented in Fig. 5 is similar to the first stage of the algorithm presented in Fig. 4 (stage 1, 2, 4), the training sample is built on the basis of balance reliability indicators. In the second part, based on the new training sample, a machine learning model is built, where the input parameters are similar to the parameters of the first algorithm, but the reliability indicators of the analyzed microgrid must be obtained as output parameters. Experimental studies of the proposed algorithms for assessing system reliability were carried out on the IEEE 96 (24)-bus RTS (Grigg et al., 1999), the scheme of which is shown in Fig. 6.

The studies were conducted to determine the probability of shortage-free operation. They aimed to obtain the system reliability values using three algorithms, namely the traditional algorithm based on the Monte Carlo method and two algorithms using machine learning methods presented earlier in the paper. The accuracy and speed of the system reliability calculation were evaluated.

Fig. 7 demonstrates the assessment results for the probability of shortage-free operation at the nodes of the system. The initial data for all calculation options were identical, except for the special parameters required to set up the machine learning models. The evaluation time when using the analyzed algorithms was checked, the assessment time of adequacy by the studied algorithms until the required accuracy is achieved in 184 s, the algorithm of assessing system reliability based on the analysis of operating conditions of calculated states using machine learning methods take 110 s, and the algorithm of assessing system reliability based on the analysis of system reliability indices using machine learning methods need about 2 s.

As seen in Fig. 7, the results for the first two algorithms are almost identical, while the assessment speed for machine learning methods is much higher (110 s versus 184 s). This advantage will be even more noticeable for large schemes since most of the time during the assessment is spent calculating and optimizing the operating parameters of the calculated states. The results of calculation using the third algorithm for some nodes are identical to those obtained with the first two algorithms, for some nodes however, they differ. One explanation for the difference is an insufficiently complete training set. The assessment time of the third algorithm, as expected, is the minimum of all, it took only 2 s to assess the reliability of the system under study, but in this case, we should not forget that the implementation of the third algorithm requires significant preparation, which can take quite a lot of time.

6. Conclusions

Ensuring the reliability of the power supply is one of the main tasks in the management of power systems. Today, distribution networks are the most unreliable link in the technological chain of the power system. At present, distribution networks receive

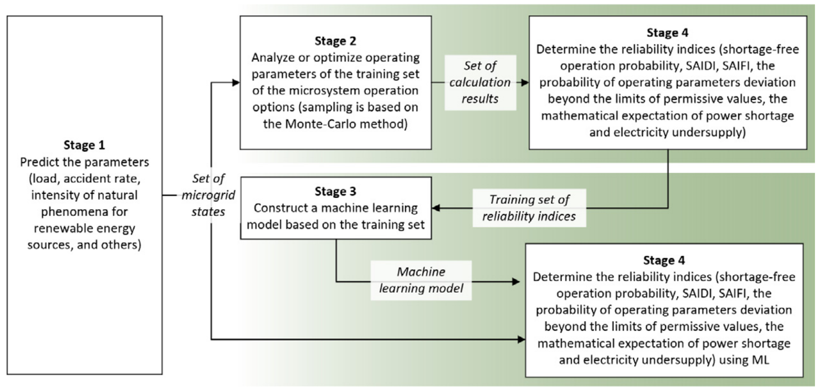

Fig. 5. Algorithm for assessing system reliability based on the analysis of system reliability indices using machine learning methods.

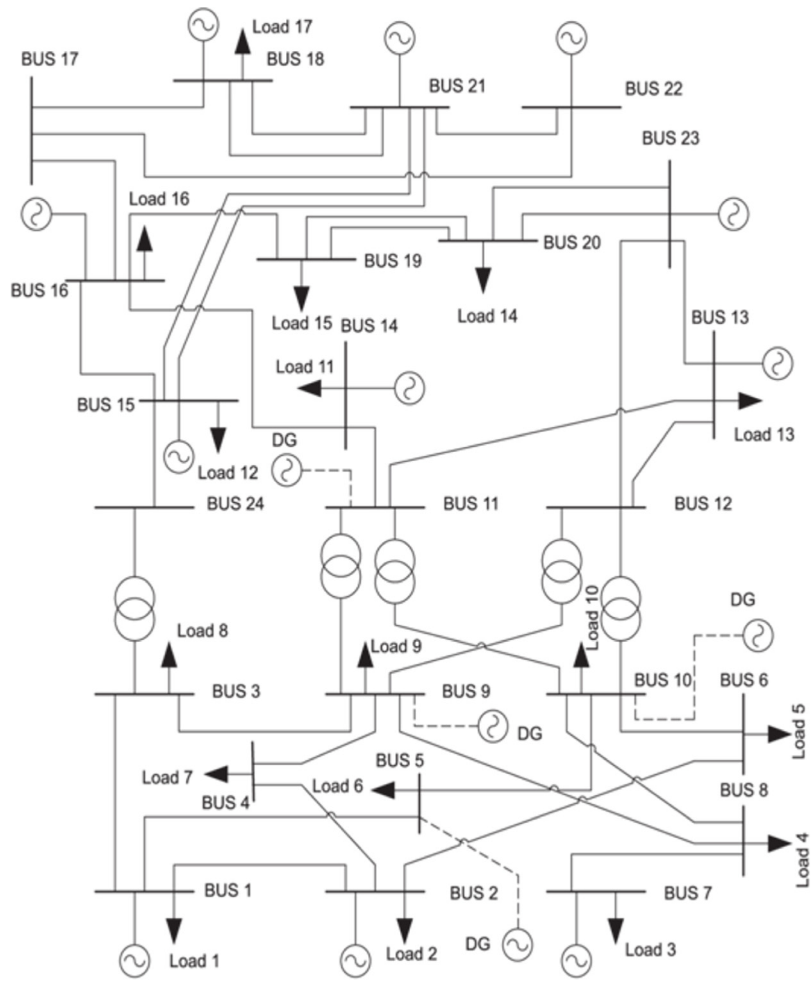

Fig. 6. IEEE 96(24)-bus RTS scheme used for experimental studies.

technical and organizational elements of activity, and microsystems are formed on their basis. Some ways of increasing the level of microgrid reliability are: (i) to create digital platforms aimed at collecting, processing, and storing the necessary information about power equipment and microgrid operating conditions; (ii) forecasting parameters related to the reliability of microgrids and their equipment; (iii) assessing reliability; and (iv) developing control actions. This assumes different ways of interaction between the digital platform and controlled/controlling entities: an assistant supervisory operator, direct automated control of distribution networks; and signals to electricity and power consumers about the risk of accidents occurring in networks. For the effective operation of digital platforms, several principles should be followed, the key among which are adaptability, continuity, parallelism, security, and customer-centricity. Even though there are quite a few technological and organizational barriers hindering the implementation of reliability management solutions for distribution networks, this way is the most effective and appropriate. The effective implementation of solutions for the development of digital reliability management platforms and their integration into distribution networks is possible only in close

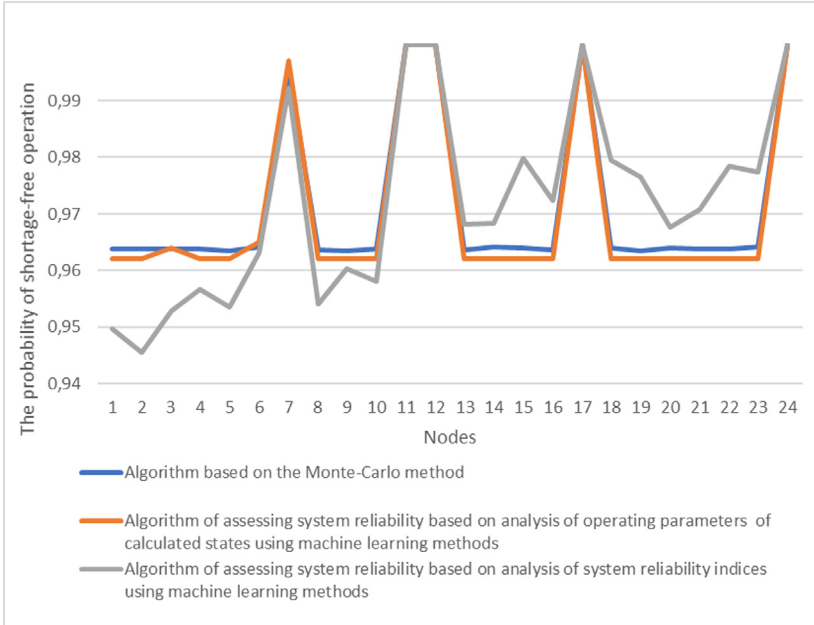

Fig. 7. The results of the IEEE 96(24)-bus RTS assessment of shortage-free operation probability.

cooperation with companies involved in scientific research and manufacturing activities. One of the main tasks in the structure of microsystem reliability control system is that of assessing the reliability for various time stages of control. To effectively assess the reliability of microsystems, it is advisable to use artificial intelligence methods (machine learning), which allow the reliability to be assessed within a reasonable time frame and with the required accuracy. The article proposes two algorithms for assessing system reliability based on machine learning methods. Both algorithms are based on a system reliability assessment technique using the Monte Carlo method. In the first algorithm, machine learning methods are used to analyze the calculated states of microsystems; in the second they are used for direct analysis of microsystem reliability indicators. Experimental studies of the proposed algorithms have shown that the estimates of system reliability, set to increase the speed while maintaining the required accuracy, have been achieved.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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