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ASSESSMENT AND ANALYSIS OF RELIABILITY INDICATORS IN POWER SUPPLY SYSTEMS WITH INTEGRATED DISTRIBUTED GENERATION SOURCES

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Abstract. This paper presents an assessment and analysis of the reliability indicators of power supply systems integrated with distributed generation (DG) sources. The increasing penetration of distributed generation, particularly renewable energy sources, has significantly changed the operating conditions of modern distribution networks and created new challenges for reliability evaluation. In this study, the reliability performance of the power supply system was analyzed using the Monte Carlo simulation method. The main reliability indices, including SAIDI (System Average Interruption Duration Index), SAIFI (System Average Interruption Frequency Index), CAIDI (Customer Average Interruption Duration Index), and ENS (Energy Not Supplied), were evaluated for systems with and without distributed generation. The simulation results demonstrate that the integration of distributed generation reduces the frequency and duration of power interruptions, decreases the amount of unsupplied energy, and improves the continuity of electricity supply to consumers. The study confirms that the proper integration of distributed generation sources enhances the operational efficiency and reliability of power supply systems. The obtained results can be used to improve the planning, operation, and reliability assessment of modern electrical distribution networks.



Keywords. Distributed generation, power supply system, reliability assessment, Monte Carlo simulation, SAIDI, SAIFI, CAIDI, Energy Not Supplied (ENS).

Annotatsiya. Ushbu maqolada taqsimlangan generatsiya (DG) manbalari integratsiyalashgan elektr ta'minoti tizimlarining ishonchlilik ko'rsatkichlarini baholash va tahlil qilish masalalari ko'rib chiqilgan. Taqsimlangan generatsiya, ayniqsa qayta tiklanuvchi energiya manbalarining keng joriy etilishi zamonaviy taqsimlash tarmoqlarining ishlash sharoitlarini sezilarli darajada o'zgartirib, ishonchlilikni baholashda yangi muammolarni yuzaga keltirmoqda. Tadqiqotda elektr ta'minoti tizimining ishonchliligi Monte-Karlo modellash usuli yordamida tahlil qilindi. SAIDI (uzilishlarning o'rtacha davomiyligi indeksi), SAIFI (uzilishlarning o'rtacha chastotasi indeksi), CAIDI (uzilishlarning o'rtacha davomiyligi indeksi) hamda ENS (iste'molchiga yetkazib berilmagan energiya) ko'rsatkichlari taqsimlangan generatsiya mavjud va mavjud bo'lmagan holatlar uchun baholandi. Natijalar taqsimlangan generatsiyaning uzilishlar soni va davomiyligini kamaytirishi, yetkazib berilmagan energiya miqdorini qisqartirishi hamda iste'molchilarga elektr energiyasini uzluksiz yetkazib berish ishonchliligini oshirishini ko'rsatdi. Tadqiqot natijalari zamonaviy taqsimlash tarmoqlarini rejalashtirish, ekspluatatsiya qilish va ishonchliligini baholashni takomillashtirishda qo'llanilishi mumkin.

Kalit so'zlar: taqsimlangan generatsiya, elektr ta'minoti tizimi, ishonchlilikni baholash, Monte-Karlo modellash usuli, SAIDI, SAIFI, CAIDI, iste'molchiga yetkazib berilmagan energiya (ENS).

Аннотация. В данной статье рассматриваются вопросы оценки и анализа показателей надежности систем электроснабжения с интегрированными источниками распределенной генерации (DG). Широкое внедрение распределенной генерации, особенно возобновляемых источников энергии, существенно изменило условия функционирования современных распределительных электрических сетей и поставило новые задачи в области оценки надежности. В работе надежность системы электроснабжения исследована с использованием метода моделирования Монте-Карло. Для систем с распределенной генерацией и без нее были определены основные показатели надежности: SAIDI (средняя продолжительность отключений), SAIFI (средняя частота отключений), CAIDI (средняя продолжительность одного отключения) и ENS (недоотпуск электрической энергии). Результаты моделирования показали, что интеграция распределенной генерации способствует снижению частоты и продолжительности отключений, уменьшению объема недоотпущенной электроэнергии и повышению надежности электроснабжения потребителей. Полученные результаты могут быть использованы при планировании, эксплуатации и оценке надежности современных распределительных электрических сетей.

Ключевые слова: распределенная генерация, система электроснабжения, оценка надежности, метод моделирования Монте-Карло, SAIDI, SAIFI, CAIDI, недоотпуск электрической энергии (ENS).



INTRODUCTION

In modern electric power systems, reliability is considered one of the most important technical and economic indicators determining the efficiency and stability of power system operation [1–4]. The reliability of a power supply system reflects its ability to continuously provide consumers with electrical energy of the required quantity and quality under both normal and emergency operating conditions [1–3]. Ensuring uninterrupted power supply is particularly important for industrial enterprises, critical infrastructure facilities, and residential consumers, since power interruptions may lead to significant economic losses, technological failures, and reductions in production efficiency. The continuous growth in electricity demand, rapid industrialization, urbanization, and the increasing complexity of modern energy systems further enhance the importance of reliability assessment and improvement. In recent years, distributed generation (DG) sources, especially renewable energy systems such as solar photovoltaic and wind power plants, have been widely integrated into electric power networks. The large-scale penetration of distributed generation fundamentally changes the structure and operating principles of traditional centralized power supply systems and requires the development of new approaches for system management, planning, and reliability evaluation [8–10]. Unlike conventional centralized generation, distributed generation units are located close to consumers, thereby reducing transmission and distribution losses, improving voltage regulation, increasing system flexibility, and enhancing the overall resilience of the power network under fault conditions. Furthermore, DG systems can serve as backup power sources during fault conditions and contribute to the continuity of electricity supply for critical loads.

At the same time, the integration of distributed generation introduces a number of technical and operational challenges. The intermittent and stochastic nature of renewable energy sources, bidirectional power flows, changes in fault current levels, and the complexity of coordination between protection and automation devices complicate the operation and control of modern power systems [5,6]. Therefore, comprehensive reliability assessment methods based on probabilistic and statistical approaches become increasingly important for analyzing the impact of distributed generation on power supply systems.

The reliability of electric power systems is directly related to system stability, operational safety, and economic efficiency. In reliability theory, the ability of a system to maintain acceptable operating conditions over a specified period of time is generally evaluated using probabilistic models, mathematical statistics, and reliability indices. Such approaches allow researchers and engineers to analyze the behavior of power system components under different operating scenarios, estimate interruption frequencies and durations, and determine the effectiveness of distributed generation integration in improving overall system performance.

METHODS

Reliability Indicators and Assessment Methods of Power Supply Systems. In international practice, the reliability of power supply systems is evaluated based on the IEEE 1366 standard [3]. This standard defines the main indicators for assessing the



frequency and duration of interruptions in electric distribution networks. The most widely used indices are SAIDI, SAIFI, and CAIDI [4]. SAIDI (System Average Interruption Duration Index) represents the average time during which consumers remain without electrical power and is determined as follows:

$$SAIDI = \frac{\sum U_i N_i}{N_{total}} \quad (1)$$

Here, U_i — denotes the interruption duration, N_i — represents the number of affected consumers, and, N_{total} — is the total number of consumers.

SAIFI (System Average Interruption Frequency Index) represents the frequency of interruptions and is expressed as follows:

$$SAIFI = \frac{\sum N_i}{N_{total}} \quad (2)$$

This indicator reflects the average number of interruptions experienced by consumers in the system [4,7]. CAIDI (Customer Average Interruption Duration Index) characterizes the average duration of a single interruption and is determined as follows:

$$CAIDI = \frac{SAIDI}{SAIFI} \quad (3)$$

In addition, additional indicators such as ENS (Energy Not Supplied) and ASAI (Average Service Availability Index) are also used for a more comprehensive assessment of system reliability. The ENS indicator determines the amount of energy not supplied to consumers and is of significant importance in evaluating economic losses.

$$ENS = \sum_{i=1}^n P_i \cdot P_{avg} \cdot t_i \quad (4)$$

Here, P_i - the average load during the interruption (kW or MW), t_i - is the interruption duration (hours), and P_{avg} - is the average load of a single consumer.

The structural configuration of power supply systems also has a significant impact on system reliability [6–11]. In series systems, the failure of a single element causes the entire system to stop operating, and the overall reliability is determined as follows:

$$R = \prod R_i \quad (5)$$

In parallel systems, reserve elements are available, resulting in higher system reliability:



$$R = 1 - \prod(1 - R_i) \quad (6)$$

Practical electrical networks usually consist of mixed (combined) structures.

In evaluating the reliability of power supply systems, the main focus is placed on the failure probability and restoration characteristics of system components [2–11]. This process is described through the following main parameters: failure rate (λ), restoration rate (μ), mean time between failures (MTBF), and mean time to repair (MTTR). Based on these parameters, the probability of system operation is determined using the following exponential law:

$$R(t) = e^{-\lambda t} \quad (7)$$

The availability factor represents the probability of the system being in an operating condition and is determined as follows:

$$A = \frac{MTBF}{MTBF + MTTR} \quad (8)$$

Distributed generation significantly affects the reliability of power supply system when integrated into the electrical network. This impact is twofold: when properly organized, distributed generation improves system reliability, while improper management may lead to various operational problems [9–10].

From a positive perspective, distributed generation sources produce electrical energy close to consumers, which reduces transmission line losses and decreases the impact of faults occurring over long distances. In addition, since distributed generation systems are capable of operating in autonomous (islanding) mode, critical consumers can continue receiving electricity even when interruptions occur in the main grid [9]. Distributed generation sources also serve as additional backup power supplies, especially during peak load periods, thereby supporting system operation. Furthermore, they increase system flexibility and enable voltage and reactive power control through the use of modern inverter technologies.

On the other hand, the presence of distributed generation sources complicates the operation and control of electrical networks. Since traditional relay protection systems are designed for unidirectional current flow, the integration of distributed generation sources may cause their improper operation. Moreover, because renewable energy sources such as solar and wind power are intermittent in nature, there is a possibility of voltage and frequency instability. Distributed generation sources also affect short-circuit currents, making equipment selection more difficult. In addition, inverter-based systems may deteriorate power quality and lead to harmonic distortions. In general, if distributed generation is properly designed and implemented together with modern control systems, it can significantly improve the reliability of power supply systems. Otherwise, it may negatively affect overall system stability.

Reliability Assessment Methods

Various methods are used to evaluate the reliability of power supply systems. These methods are selected depending on system complexity, available data, and research objectives. The main methods include deterministic, probabilistic-statistical, Monte Carlo, and Markov models.



The deterministic method is one of the simplest and most classical approaches used in the reliability assessment of power supply systems and is based on the “N-1” criterion. According to this criterion, the system must continue supplying consumers with electrical energy even if any single component of the system (transformer, transmission line, or generator) fails.

According to this approach, each component is considered important, and its failure significantly affects system operation. Therefore, the system must contain reserve paths or alternative power transmission capabilities. In emergency situations, the load is redistributed through other system components [2-5].

This criterion is mathematically expressed through the power balance equation:

$$\sum P_{gen} - P_{loss} \geq P_{load} \quad (8)$$

The main advantage of the deterministic method lies in its simplicity and fast calculation capability. Therefore, it is considered convenient for preliminary assessment during the design stage.

However, this method does not take into account the probabilistic nature of failures and does not reflect random processes occurring under real operating conditions. For this reason, in complex systems it is recommended to use it together with probabilistic and simulation methods.

The probabilistic-statistical method is a modern approach used in evaluating the reliability of power supply systems, which considers the failure probability and time-dependent operating characteristics of system components. Unlike the deterministic method, this approach takes into account random processes occurring during real operation and provides a more accurate assessment of system conditions.

The main parameter is the failure rate λ , which is determined as the ratio of the number of failures to time. The probability of system operation is evaluated based on the exponential law.

Since this method is based on real statistical data, it is considered practically effective. However, it requires a large amount of reliable statistical information; otherwise, the accuracy of the results may decrease.

Markov models are mathematical approaches used in the reliability assessment of power supply systems and are based on system states and transition probabilities between these states.

In this model, the system consists of several states (operational, failed, and restoration), and transitions between them are represented through certain probabilities or intensities. Using this approach, the time-dependent condition and reliability level of the system can be determined.

Markov models are especially effective in considering restoration processes. However, as the system becomes more complex, the number of states increases, making the calculation process more difficult. Therefore, this method is often applied to simplified systems.

The Monte Carlo method is one of the most advanced and highly accurate simulation techniques used for evaluating the reliability of power supply systems. This



method is based on probability theory and assesses system operation through repeated random simulations.

The essence of the Monte Carlo method is that failures and restoration processes of system components are generated using random numbers. During each simulation process, the state of the system is determined, and this process is repeated thousands or even millions of times. As a result, the obtained data are statistically processed to determine the overall reliability indicators of the system [6–7].

The main advantage of this method is its ability to accurately model complex and large-scale electrical systems. In particular, the Monte Carlo method is highly effective for systems integrated with distributed generation sources (solar and wind energy), since it also takes into account the variability of power generation.

In this study, the Monte Carlo simulation method based on a probabilistic-statistical approach was applied to evaluate the reliability of power supply systems integrated with distributed generation sources. The main reason for selecting this method is related to the random nature of failures and restoration processes of electrical system components, as well as the necessity of considering the variable generation characteristics of distributed generation sources.

Within the framework of the research, a distribution network with a voltage level of 6–10 kV was considered as the model system. In addition to transmission lines, transformers, and consumers, the network also included a distributed generation source represented by a solar photovoltaic power plant. The system was analyzed under the following two conditions:

1. Without distributed generation (traditional system)
2. With integrated distributed generation sources

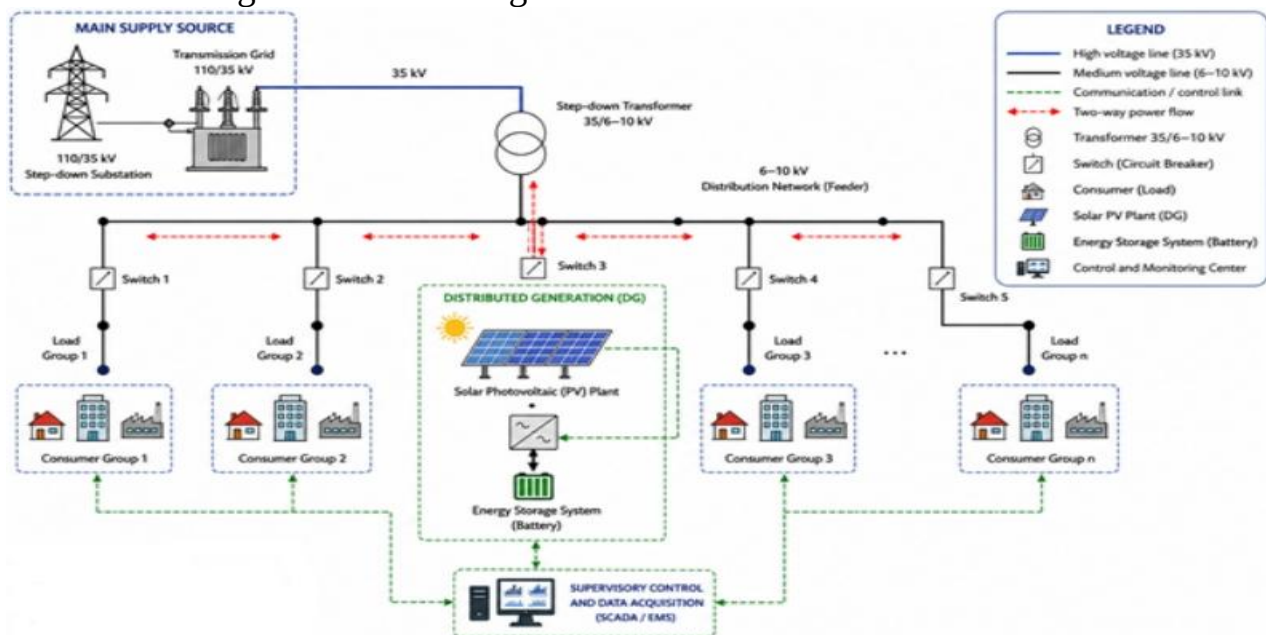


Figure 1. Structural diagram of a power supply system integrated with distributed generation sources

During the simulation process, the operating condition of system components was modeled based on the following main parameters: failure rate (λ) – the probability



of component failure (1/year), restoration rate (μ) – the speed of component restoration (1/hour), mean time to repair (MTTR), load level (P_{load}), and distributed generation output power (P_{DG}).

During the Monte Carlo simulation, the failure and restoration states of each component were determined using a random number generator, and the overall operating condition of the system was evaluated. The calculation process was carried out based on 1000 iterations, which made it possible to obtain statistically reliable results.

In each iteration, the number of interruptions occurring in the system, interruption duration, and the number of affected consumers were determined. Finally, the following reliability indicators were calculated: SAIDI, SAIFI, and ENS (Energy Not Supplied).

RESULTS

Within the framework of the study, the reliability indicators of the power supply system were evaluated for cases with and without distributed generation based on Monte Carlo simulation. The simulation results demonstrated that distributed generation sources have a significant positive impact on system reliability.

According to the obtained results, the system without distributed generation exhibited higher interruption frequency and duration, while the amount of unsupplied energy to consumers was also relatively large. In the case where distributed generation sources were integrated into the system, the load was partially supplied by local generation, thereby reducing the impact of interruptions on consumers [1-3].

In particular, in the system with distributed generation: the interruption duration decreased, the interruption frequency was reduced, and the amount of unsupplied energy significantly declined.

These results can be explained by the proximity of distributed generation sources to consumers and their capability to operate autonomously. Especially in radial distribution networks, distributed generation sources were found to be effective tools for protecting critical loads from interruptions. At the same time, the simulation results also showed that voltage stability and control issues are of great importance in systems integrated with distributed generation. If distributed generation is improperly controlled or if system protection devices are not properly coordinated, the reliability indicators may not improve to the expected level [6-7].

In general, the obtained results confirm that distributed generation is an effective solution for improving reliability in power supply systems; however, its effectiveness depends on proper integration and the application of modern control systems.

A distribution network consisting of 1000 consumers was considered as the study system. As a result of the simulation, the following interruptions were recorded:

Interruption 1: lasted 2 hours and affected 300 consumers.

Interruption 2: lasted 1 hour and affected 200 consumers.

1. SAIDI calculation:

$$SAIDI = \frac{\sum U_i N_i}{N_{total}} = \frac{(2 \cdot 300) + (1 \cdot 200)}{1000} = 0.8 \text{ hour}$$

2. SAIFI calculation:

$$SAIFI = \frac{\sum N_i}{N_{total}} = \frac{300 + 200}{1000} = 0.5$$



3. CAIDI calculation: $CAIDI = \frac{SAIDI}{SAIFI} = \frac{0.8}{0.5} = 1.6 \text{ hour}$

4. ENS calculation: Average load of 1 kW per consumer.

$$ENS = \sum P_i \cdot t_i = (300 \cdot 1 \cdot 2) + (200 \cdot 1 \cdot 1) = 800 \text{ kWh}$$

In the presence of distributed generation sources, the results were as follows:

Interruption 1: reduced from 2 hours to 1.2 hours, affecting 200 consumers.

Interruption 2: reduced from 1 hour to 0.5 hours, affecting 150 consumers.

1. SAIDI calculation: $SAIDI = \frac{\sum U_i N_i}{N_{total}} = \frac{(1.2 \cdot 200) + (0.5 \cdot 150)}{1000} = 0.315 \text{ hour}$

2. SAIFI calculation: $SAIFI = \frac{\sum N_i}{N_{total}} = \frac{200 + 150}{1000} = 0.35$

3. CAIDI calculation: $CAIDI = \frac{SAIDI}{SAIFI} = \frac{0.315}{0.35} = 0.9 \text{ hour}$

4. ENS calculation:

$$ENS = \sum P_i \cdot t_i = (200 \cdot 1 \cdot 1.2) + (150 \cdot 1 \cdot 0.5) = 315 \text{ kWh}$$

Table 1. Comparison Table of Results

Indicator	Without DG	With DG	Change
SAIDI	0.8 hour	0.315 hour	↓ 60%
SAIFI	0.5	0.35	↓ 30%
CAIDI	1.6 hour	0.9 hour	↓ 44%
ENS	800 kWh	315 kWh	↓ 60%

Figure 2 compares the main reliability indicators of the power supply system — SAIDI, SAIFI, and CAIDI — for cases with and without distributed generation. As can be seen from the graph, all indicators significantly decreased after the integration of distributed generation. In particular, the reduction in SAIDI and CAIDI values indicates a decrease in interruption duration, while the reduction in SAIFI demonstrates a decrease in interruption frequency. These results confirm the positive impact of distributed generation on improving the reliability of power supply systems [3].

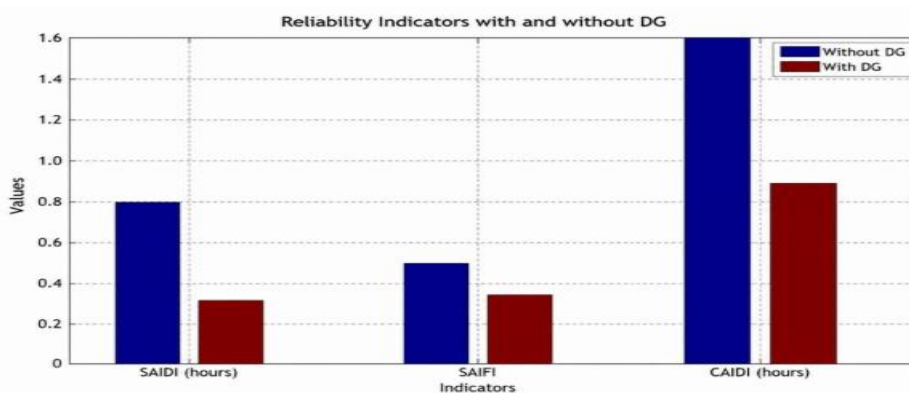


Figure 2. Comparison of reliability indicators in cases with and without distributed generation.



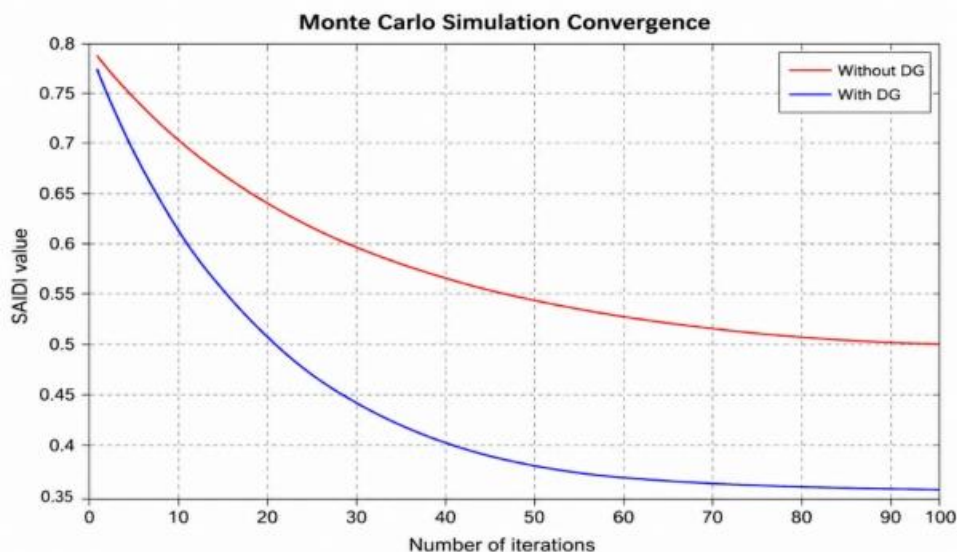


Figure 3. Convergence of the SAIDI indicator based on Monte Carlo simulation.

Figure 3 illustrates the variation of the SAIDI indicator over simulation iterations obtained through the Monte Carlo method. As can be observed from the graph, the results become more stable and converge as the number of iterations increases. In the case with distributed generation, the SAIDI value is formed at a significantly lower level compared to the system without distributed generation, which indicates that distributed generation reduces interruption duration. Furthermore, the faster stabilization of the results confirms the reliability of the model and the accuracy of the simulation.

The calculation results show that distributed generation has a significant positive impact on the operational efficiency and reliability of the power supply system. In particular, in the presence of distributed generation, the impact of interruptions on consumers decreases, while both the duration and coverage of interruptions are reduced, leading to lower SAIDI and CAIDI values.

In addition, the presence of local energy sources improves the quality of electricity supply, meaning that voltage levels become more stable and the system operates more flexibly under varying load conditions. As a result, the continuity of electricity supply to consumers is improved.

In general, distributed generation increases the overall reliability level of the system, reduces the number and duration of interruptions, and ensures the stable operation of the power supply system.

CONCLUSION

In this study, the reliability indicators of power supply systems integrated with distributed generation sources were evaluated using the Monte Carlo simulation method. The obtained results confirmed that distributed generation has a significant positive impact on system reliability.

The calculation results showed that, in the presence of distributed generation, the SAIDI indicator decreased from 0.8 hours to 0.315 hours (approximately 60%), SAIFI decreased from 0.5 to 0.35 (30%), and CAIDI decreased from 1.6 hours to 0.9 hours



(44%). In addition, the amount of energy not supplied (ENS) decreased from 800 kWh to 315 kWh, indicating an improvement in the economic efficiency of the system.

The analysis demonstrated that distributed generation reduces the impact of interruptions due to its proximity to consumers, supports local loads, and increases system flexibility. In particular, in radial distribution networks, distributed generation sources proved to be effective tools for protecting critical loads against interruptions.

At the same time, the research results showed that the effectiveness of distributed generation depends on its proper integration, modern control systems, and coordinated relay protection devices. In cases of improper control, system stability may decrease. For future research, it is recommended to expand the study by including energy storage systems, improving the model based on real operational data, and further investigating system reliability through the implementation of Smart Grid technologies.

The proposed methodology provides a practical framework for improving the reliability of modern power supply systems and can support decision-making in the planning, operation, and optimization of future Smart Grid distribution networks with integrated distributed generation sources.

REFERENCES

1. Karimov A.A., Rakhimov B.T. Power Supply Systems. Tashkent: Science and Technology Publishing House, 2018.
2. Abdullayev O.X. Electric Power Systems and Networks. Tashkent: Teacher Publishing House, 2016.
3. Tursunov X.T. Reliability of Power Supply Systems. Tashkent: Science Publishing House, 2019.
4. Yusupov M.A. Fundamentals of Electrical Network Design. Tashkent: Science and Technology Publishing House, 2017.
5. IEEE Std 1366-2023. IEEE Guide for Electric Power Distribution Reliability Indices. IEEE Standards Association, 2023.
6. Ali, A., Hussain, S. M. S., Ustun, T. S., Ali, I. Recent advances in distributed generation integration and its impact on power system reliability: A review. *Energies*, vol. 17, no. 2, Article 356, 2024.
7. Lopes J. A. P., Hatziargyriou N., Mutale, J., Djapic, P., Jenkins N. "Integrating Distributed Generation into Electric Power Systems," *Electric Power Systems Research*, vol. 77, pp. 1189–1203, 2017.
8. Tercan S. M. A comprehensive review of recent advances in optimal allocation methods for distributed renewable generation. *IET Renewable Power Generation*, vol. 17, no. 13, pp. 4098–4135, 2023.
9. Kumar A., Verma R., Choudhary N. K., Singh N. Optimal placement and sizing of distributed generation in power distribution system: A comprehensive review. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45, no. 3, pp. 7160–7185, 2023.
10. Hines P., Apt, J., Talukdar S. "Large Blackouts in North America: Historical Trends and Policy Implications," *Energy Policy*, vol. 37, pp. 5249–5259, 2019.
11. Supply Systems," *Journal of Energy of Uzbekistan*, 2020, No. 2, pp. 45–52.

