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## SIMULATION OF THE INTEGRATION OF A SOLAR POWER PLANT INTO A 10/0.4 KV DISTRIBUTION NETWORK USING THE SICAD PLATFORM

The intensive development of renewable energy in Ukraine and the world necessitates an in-depth study of the processes of integration of solar power plants into medium-voltage distribution networks. Increasing the share of decentralized generation sources changes the established modes of operation of electrical systems, makes it difficult to balance active and reactive power, affects the voltage level in nodes and creates additional requirements for protection and automation systems. The relevance of the problem is enhanced by the fact that networks of voltage class 6 – 10 kV were originally designed to work in the traditional direction of power flows – from the substation to consumers, while the connection of solar stations causes the appearance of reverse flows and uneven load distribution. The purpose of this study is to model the impact of photovoltaic plants on the operation of distribution networks and analyze the capabilities of inverters in increasing the efficiency of voltage regulation and maintaining the reliability of power supply. The object of the study is a 10/0.4 kV distribution network with a 5 MW integrated solar power plant, reproducing a typical example of a modern renewable source system. The main hypothesis is that the use of inverters with a reactive power control algorithm ensures the stability of operating modes and reduces the negative consequences of fluctuations in solar generation. The work adopts a comprehensive approach including analytical methods for calculating power flow distribution and computer simulations in the SICAD software environment. This made it possible to reproduce the operation of the network in various scenarios: at the night minimum load, the daytime peak of generation, as well as in transient modes. In addition, emergency situations were investigated, including a sudden shutdown of the solar power plant and the occurrence of short circuits. This approach makes it possible to assess not only the standard, but also the emergency conditions of the system's functioning. The scientific novelty of the work consists in the development of an approach to assessing the impact of photovoltaic power plants on the modes of operation of distribution electric networks, taking into account the possibilities of controlling the reactive power of inverters and the variable nature of solar generation. The practical significance of the results lies in the possibility of their use for the development of methodological recommendations for the integration of photovoltaic plants in medium voltage networks, as well as for the improvement of inverter control algorithms. The obtained conclusions can be useful both to operators of distribution systems and project organizations when planning the development of electrical networks, taking into account the growing share of renewable energy sources.

**Keywords:** electrical distribution network; solar power plant; photovoltaic generation; inverter; voltage regulation; reactive power; computer simulation.

**Introduction.** Current energy development is inextricably linked to global environmental challenges, reduced carbon dioxide emissions and the transition to a sustainable economy. In these conditions, renewable energy sources, in particular solar power plants (SPPs), are gaining more and more importance. There has been a steady trend in the world towards an increase in their share of the overall generation balance sheet, which is attributable to the environmental benefits, economic feasibility and technical capacity for rapid deployment of such facilities. Ukraine is also actively moving in this direction, as the integration of renewable generation is an important component of the state's energy security and its international obligations within the framework of the «green» transition.

However, the wide implementation of SPP in medium voltage distribution networks is accompanied by a number of new problems. In a traditional power supply system, power flows had a one-way – direction from large

generating stations to consumers. In the conditions of connecting SPPs, this nature changes, which makes it difficult to regulate network operation modes. In addition, the generation of electricity from solar radiation is unstable in nature, as it depends on weather conditions, which can cause significant voltage fluctuations. An additional risk factor is the influence of inverters on the quality of electricity: the appearance of harmonic components, flickers and possible deterioration of phase symmetry. All this poses a threat to the reliability and safety of distribution networks, which were originally designed for classic consumption conditions.

That is why there is a need to conduct scientific research aimed at studying the impact of SPP on the modes of operation of distribution networks. This makes it possible to identify potential problems in advance and find optimal technical solutions to minimize them. In addition, the results of such studies could provide a basis for improving the regulatory framework, improving the planning efficiency of

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new generation facilities and upgrading already existing networks. Also, modeling the operation of the system in specialized software environments, such as SICAD [1], allows you to assess with high accuracy the impact of connecting renewable sources on power supply parameters, ensure the stability of the system in regular and emergency modes, and develop recommendations for increasing the reliability of energy supply.

The practical significance of such research lies in the creation of scientifically based methodical approaches to the integration of SPP in medium voltage networks. This contributes to reducing operating costs, reducing electricity losses, improving voltage quality and ensuring stable operation of the electric power system in general. At the same time, the study provides the possibility of formulating recommendations for energy companies and distribution system operators, which will allow more efficient management of the process of connecting new generating facilities.

Therefore, the scientific problem of integrating SPPs into medium voltage distribution networks is extremely relevant both from the point of view of ensuring energy stability and safety, and in view of the practical tasks of increasing the efficiency and quality of electricity supply. Therefore, studies dedicated to simulating the integration of SPPs in a 10/0.4 kV distribution network using the SICAD software environment and the analysis of system operating modes are relevant.

**Analysis of literary sources and formulation of the problem.** In the work [2], a broad review study of the development of SPPs integration into energy networks was carried out and the main directions and problem areas of integration were identified (in particular, issues of electricity quality, losses, voltage modes). However, the work is of a generalised nature and does not contain a detailed analysis of emergency mode scenarios or an application model for 10 kV medium voltage networks.

In study [3], the influence of reverse flows on transformers and other network elements was analyzed using the example of low-voltage networks, and the risks of transformer overload with a large share of SPP were revealed. However, the results mainly concern low voltage networks and are not directly transferred to the features of 10 kV medium voltage networks, where other topology and mode characteristics.

The work [4] presents a number of applied studies and methods for assessing the impact of SPPs on medium voltage networks (voltage analysis, losses, optimal placement), and reveals a positive effect of local load coverage. However, the study rarely includes a detailed assessment of dynamic responses to accidents (sudden generation outages) and interaction with relay protection.

The publication [5] focuses on the measurement and theoretical analysis of the phenomena of voltage reduction or increase during reverse flows in feeders, demonstrating that standard voltage regulators can experience problems with a high level of SPPs penetration. However, the work does not cover the impact of realistic daily and seasonal solar insolation profiles and does not make practical recommendations for tuning inverters in 10 kV networks.

The study [6] considered strategies for placing and selecting SPP power in the distribution network environment in order to minimize losses and improve the voltage profile. The usefulness of optimal placement is shown. However, the work applies static scenarios and does not simulate emergency modes or features of inverter dependency control algorithms «reactive power – voltage».

Publication [7] analyzed approaches to control the reactive power of inverters (dependency regulation «reactive power – voltage», power factor regulation, etc.) as a voltage stabilization tool. The effectiveness of such methods in regular regimes has been proven. However, many studies are limited to idealized models of inverters and do not take into account their behavior in emergency transitions or in rapidly changing generation modes.

In work [8], the issue of SPP modeling in dynamic models is considered, standardized approaches to the display of inverters and solar arrays are given. However, the practical application of these models at the level of medium voltage networks of 10 kV with the subject of return flows and specific feeder topologies is often not presented in the form of a ready-made technique for engineers.

The work [9] provides an overview of the impact of the high level of penetration of dispersed energy sources (in particular SPP) on the parameters of distribution networks and recommendations for the adaptation of traditional means of regulation. It is shown that modifying the controllers of voltage regulators and coordination mechanisms can facilitate integration. At the same time, the article does not provide an in-depth analysis of specific emergency scenarios typical of 10 kV networks with large SPPs.

In study [10], the issue of optimal placement and power of SPPs in long medium voltage feeders was considered and it was shown that localization and power value significantly affect voltage losses and profile. However, most studies use simplified or averaged daily insolation profiles, which reduces the accuracy of the assessment in cases of sudden weather changes and emergency outages.

The publication [11] investigated the influence of the choice of the SPP model (degree of detail of the inverter and photovoltaic modules) on the results of the analysis of the network operation; it was proved that the accuracy of the model significantly affects the conclusions regarding the quality of voltage and losses. However, the question of choosing the optimal level of detail (balance of accuracy and computational complexity) for modeling 10 kV networks is left open.

In work [12], a comparative analysis of problems with the quality of electricity in networks with a high level of SPPs penetration (harmonics, flickers, full coefficient of harmonic distortions) was performed and compensation methods were considered, but most solutions are focused on low-voltage networks and do not take into account the features of protection and coordination in 10 kV networks.

The publication [13] analysed the daily and seasonal SPP generation profiles and their impact on network mode parameters. It is shown that taking into account realistic profiles increases the correctness of calculations. However, the work does not integrate these profiles into complete accident scenarios (for example, sudden shutdown of SPPs

during peak hours) and does not consider the impact of additional means such as energy storage.

Study [14] examined practical examples of the application of software complexes for the simulation of electrical networks (OpenDSS, ETAP, PowerFactory) in order to analyse return flows and their compensation measures. It shows how such tools help in planning. However, in most cases there is a lack of in-depth validation of models on real data of 10 kV medium voltage networks and a robust strategy taking into account inverter adjustment during accidents.

Publication [15] presents optimization methods and strategies for coordinating voltage regulators, including strategies for using SPPs inverters as virtual reactive power sources. However, the practical implementation of such strategies in systems with communication disabilities and old relay protection has not been investigated.

The work [16] carried out a systematic analysis of the risks of integrating the large capacity of SPPs into distribution networks and emphasized the importance of the combined use of energy storage devices, adaptive settings of inverters and modernization of protection systems. However, practical techniques for engineering implementation (in particular, specific settings for 10 kV networks and validation algorithms in specialized software complexes) remain underdeveloped.

The analysis of the given sources [2–16] indicates a significant attention of scientists to the problems of integration of SPPs into electrical networks. Despite the variety of – approaches from generator placement optimization, voltage and loss analysis, to reactive power management and emergency mode modeling –, none of the studies offer a comprehensive applied technique for medium voltage 10 kV networks.

Existing robots are mostly either limited to low-voltage networks, or only consider individual aspects (static scenarios, individual modes, local examples), leaving out system analysis of dynamic emergency processes combined with features of inverters, relay protection and energy storage.

Thus, a common unresolved problem is the lack of a formalized model of SPP integration in a medium voltage network of 10 kV, which would comprehensively take into account emergency scenarios, the operation of inverters, relay protection and auxiliary means (energy storage).

Solving this problem will allow the creation of engineering methods to ensure the reliability, quality of electricity and safe operation of networks with a high level of SPPs penetration.

**Purpose and tasks of research.** The aim of the study is to develop a mathematical model of a 10/0.4 kV distribution network with a connected SPP in the SICAD software environment to analyze the impact of renewable generation on the operating modes of the system. This will make it possible, on the one hand, to obtain new scientific results regarding the regularities of the functioning of electrical networks in the presence of solar generation, and on the other hand, to form practical recommendations for increasing the reliability and efficiency of their operation.

To achieve the set goal, the following research tasks were defined:

- to analyse the features of the operation of 10/0.4 kV distribution networks under SPP connection conditions and to highlight the main factors affecting mode parameters;
- build a mathematical model of a distribution network with an integrated SPP in the SICAD software environment and parameterize it based on real output data;
- conduct an analysis of normal and emergency modes of system operation, assess the impact of SPP generation on voltage levels, current distribution and electricity loss, as well as develop practical recommendations for optimizing network operation.

**Research materials and methods.** The object of the study is a 10 kV voltage class electrical distribution network, powered by a 110/10 kV substation and containing traditional consumers and renewable energy sources in the form of a SPP with a nominal capacity of 5 MW. This facility is typical of modern regional-level electrical networks and allows to investigate the peculiarities of the influence of solar generation on voltage indicators, distribution of power flows and operating conditions of equipment.

The main hypothesis of the study is that the introduction of mechanisms for flexible regulation of the parameters of inverters of SPPs allows to increase the reliability and quality of power supply in distribution networks. In particular, it is assumed that reactive power regulation is able to compensate for the influence of fluctuations in solar generation and contribute to the reduction of voltage deviations.

A number of assumptions are accepted in the work. First, daily consumer load schedules are considered typical and invariant to weather conditions. Secondly, the generation profiles of a SPP are determined by the average values of insolation and temperature for a specific climatic region, which avoids the need to model random fluctuations.

Third, the SPP inverter is considered as an ideal controlled source of active and reactive power without taking into account internal nonlinear conversion processes.

A number of simplifications were also adopted. The model does not take into account fast-moving electromagnetic transients, as the main focus is on stationary and quasi-stationary modes of operation. Losses in the secondary circuits of transformers and control equipment are also not taken into account, which allows you to focus on the analysis of the main processes in the power part of the network. In addition, the network is considered as a symmetric three-phase system without taking into account the influence of load asymmetry.

The research was carried out using analytical and software methods. At the analytical stage, classical power balance equations, expressions for determining losses in lines and voltages in nodes were used. To reproduce the operation of the network in different modes, the SICAD software environment was used, which allows modeling electrical networks taking into account their topology and equipment characteristics. The model displays a single-line network diagram, includes parameters of transformers,

overhead and cable lines, as well as loads in characteristic nodes. Active power generation profiles and a reactive power control algorithm have been implemented for SPPs.

Experimental studies in the SICAD simulation software environment were carried out under several scenarios corresponding to typical network operating conditions: night minimum consumption, daytime peak generation and intermediate transient modes. In addition, to check the stability and adequacy of the model's operation, the conditions of emergency situations were laid, including a sudden shutdown of solar generation and the occurrence of a short circuit on one of the lines.

**Features of the operation of 10 kV distribution networks under the conditions of connection of SPPs.** The integration of SPPs into medium voltage distribution networks is becoming one of the key trends in the development of modern energy. 10/0.4 kV networks were traditionally built on the principle of «source – consumer», that is, they provided for the unidirectional movement of electricity from the substation to the end users. With the advent of distributed generation, in particular SPPs, new phenomena arise in these networks: a change in the direction of power flows, local overvoltages, a decrease or increase in losses, as well as an increase in requirements for the relay protection and automation system.

At any given time, an active power balance is performed for an individual network node (1):

$$P_G(t) - P_A(t) = \sum_k P_{los,k}(t), \quad (1)$$

where  $P_G(t)$  – active generation power in the node (for example, from the SPP);

$P_A(t)$  – active load power;

$P_{los,k}(t)$  – losses in network elements. If the value of  $P_G(t)$  exceeds  $P_A(t)$ , the difference is directed to the network, creating a «return flow». It is this situation that most often causes technical difficulties, since the network was designed for unidirectional energy flows.

Energy losses in distribution lines depend significantly on the current flowing through the conductors. They are described by the formula (2):

$$P_{los} = I^2 \cdot R_A, \quad (2)$$

where  $I$  – current in the line;

$R_A$  – its active resistance.

If the SPP partially or completely compensates for the local load, the current at the section «substation – node with SPP» decreases, which leads to a decrease in losses. At the same time, in the case of a significant excess of generation over consumption, new flow zones appear in the network, which can increase currents and, accordingly, losses in neighboring areas.

The most critical parameter for the reliability of consumer work is the voltage level. In classic power circuits, it gradually decreases with distance from the substation. However, in the case of SPPs, the opposite phenomenon – local voltage increase may be observed at individual points. This is explained by the expression (3):

$$\Delta U \approx I \cdot (R \cos \varphi + X \sin \varphi), \quad (3)$$

where  $\Delta U$  – voltage drop;

$R$  and  $X$  – line resistance parameters;

$\varphi$  – shear angle between voltage and current.

In the case when the consumption is small and the generation from the SPPs is large, the voltage at the connection point increases, creating risks of exceeding the regulatory limits, as shown in Fig. 1.

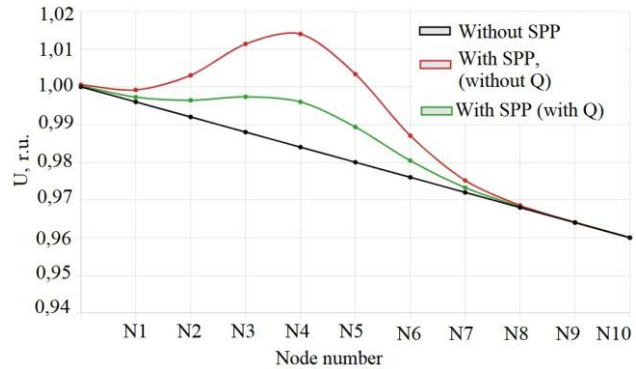


Figure 1 – Voltage profile along the feeder 10 kV (nodes № 0...10)

The level of SPP generation is diurnal and seasonal, due to insolation and temperature conditions. Equations were used for calculations in the work (4):

$$P_G(t) = P_{nom} \cdot \frac{G(t)}{G_{il}} \cdot f(t), \quad (4)$$

where  $P_{nom}$  – nominal capacity of the installation,

$G(t)$  – current solar radiation;

$G_{il} = 1000 \text{ W/m}^2$  – standard illumination,

$f(t)$  – temperature coefficient.

As can be seen from the illustrative daily schedule (Fig. 2), the maximum generation occurs at noon, while in the morning and evening hours the power of the SPP is practically zero.

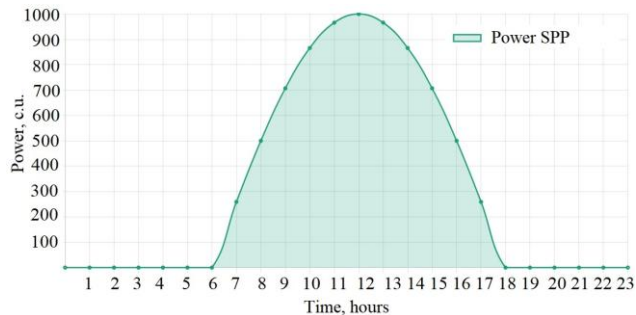


Figure 2 – Daily SPP generation profile

Modern SPPs inverters have the ability to regulate reactive power, which allows you to stabilize the voltage in the network. One common control law is described by the equation (5):

$$Q = K_{adj} \cdot (U_{ref} - U), \quad (5)$$

where  $Q$  – reactive power generated or consumed by the inverter;

$U_{ref}$  – voltage reference value;

$U$  – actual voltage value at the node;

$K_{adj}$  – adjustment factor.

The use of such an approach allows a significant reduction of overvoltages, which is confirmed graphically in Fig. 1 (green curve).

Thus, the impact of SPP on the 10/0.4 kV network is determined by a number of factors:

- the ratio between local consumption and generation;
- parameters of electric lines (supports R and X);
- features of daily and seasonal generation profiles;
- algorithms for the operation of inverters, in particular their ability to regulate reactive power.

Taking these aspects into account in the modeling process made it possible to adequately assess possible problems and find ways to solve them, including optimization of modes, selection of inverter settings and use of regulatory devices in the network.

**Construction of a mathematical model of a 10 kV distribution network with an integrated SPP in the SICAD software environment.** The development of a mathematical model is a key stage of research, as it allows you to reproduce the real conditions of operation of the electrical network and conduct a further analysis of the impact of renewable generation on its operating modes. In the work, the construction of the model is carried out in the SICAD software environment, which provides a wide range of tools for modeling energy systems.

The choice of this tool is due to its ability to comprehensively model electric power systems, take into account nonlinear characteristics of equipment, calculate stationary and dynamic modes, as well as the presence of specialized libraries for modeling renewable energy sources. The steps of the simulation process are presented in Fig. 3.

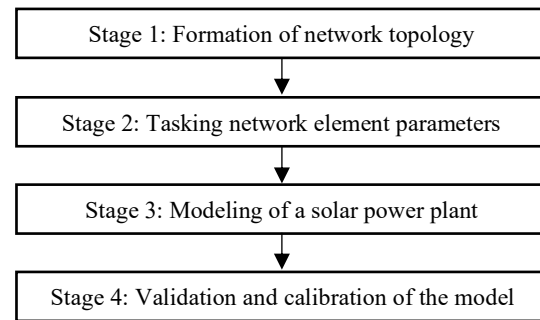


Figure 3 – Stages of the modeling process

**Stage 1: Formation of network topology.** Based on real output data (single line circuit, power lines parameters, transformer substations), a model of a typical 10/0.4 kV radial type distribution network was created. Fig. 4 is a general view of the circuit in a SICAD environment.

The model includes a 110/10 kV central substation from which a number of distribution feeders are fed. For the study, one of the feeders was chosen, to which a SPP with a capacity of 5 MW was connected at a point remote from the power source. This configuration allows the clearest analysis of the influence of distributed generation on the voltage profile and the distribution of power flows.

**Stage 2: Tasking network element parameters.** For each element of the model (air and cable power lines, transformers, switching equipment), parameters corresponding to real operating conditions were set:

- for power lines, active R and reactive X supports per unit length are specified, taking into account the wire brand, cross-section and gasket configuration;
- for substation transformers, the rated power, short-circuit voltage, idle loss and short-circuit loss are specified;
- the load in the network nodes is set in the form of active P and reactive Q power graphs, reflecting typical daily consumption profiles.

Fig. 5 shows the parameterization window of the elements in the SICAD software environment, where the characteristics of one of the transformers and the 10 kV line are given by way of example.

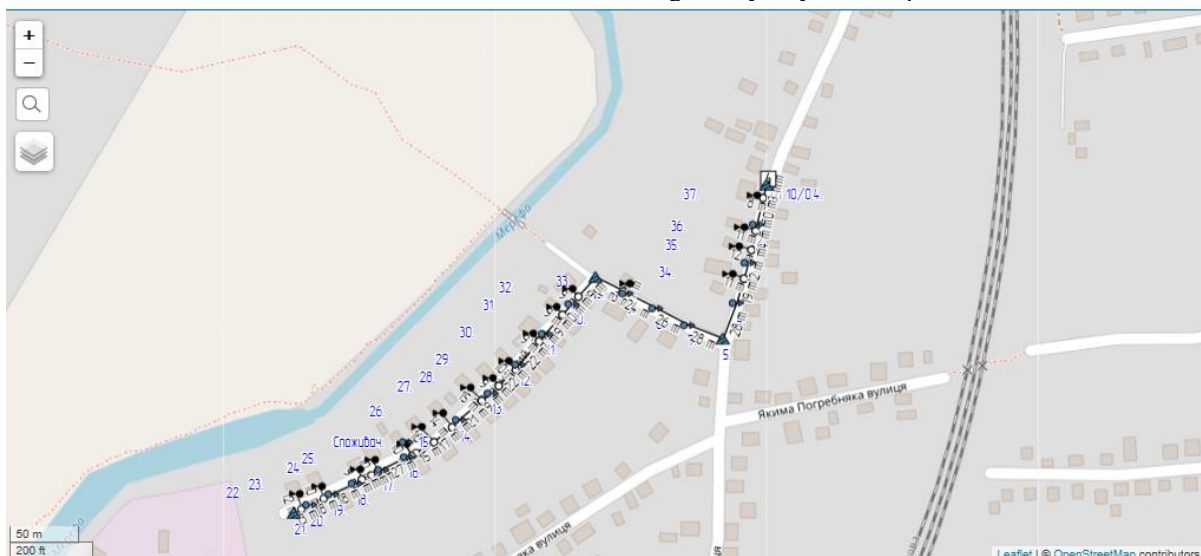


Figure 4 – Topological diagram of a 10/0.4 kV distribution network in the SICAD software environment

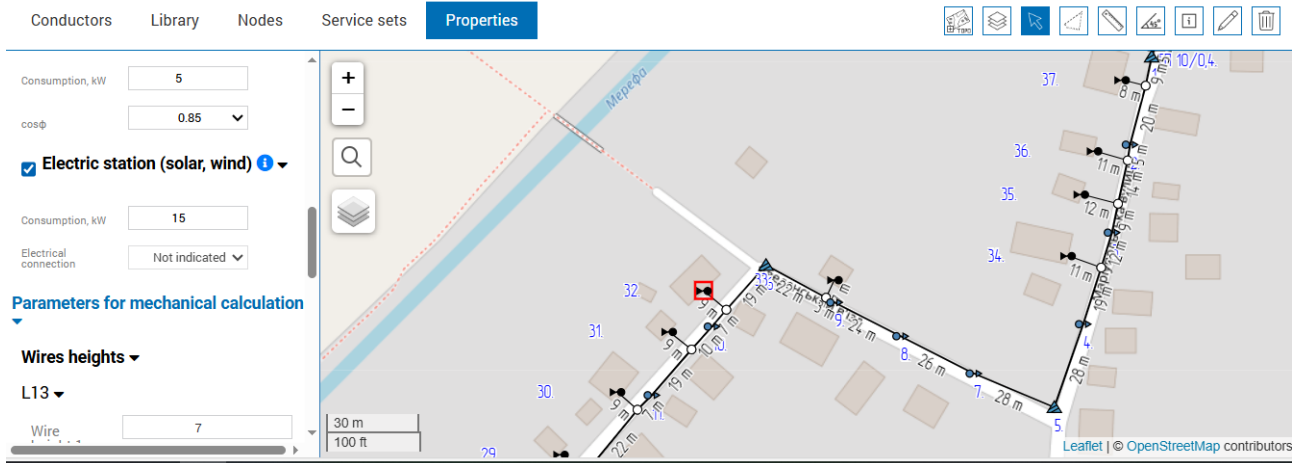


Figure 5 – Entry window for element parameters in the SICAD software environment

**Stage 3: Modeling of a SPP.** The key component of the model is the – SPP generation object. Her model at SICAD was implemented based on the following principles:

- power source: SPP is presented as a controlled source of active power, the operation of which is described by equation (4). The model generates an active power profile based on a given daily solar insolation schedule  $G(t)$  and a temperature coefficient  $f(t)$ , which allows simulating the real variability of the generator.
- inverter: An inverter model with advanced functionality was used to convert direct current from photovoltaic modules into alternating current. The inverter can operate not only in the set active power mode, but also has the ability to adjust the reactive power  $Q$  according to the control law described by Equation (5). This allows the effect of the inverter control system on voltage stabilization at the connection point to be investigated.
- protection system: The inverter model also includes standard protection functions, such as disconnection when voltage or frequency exceeds permissible limits, which is important for the analysis of emergency modes.

In the SICAD software environment, the possibility of downloading daily insolation profiles was implemented, which made it possible to create a realistic generation scenario.

**Stage 4: Validation and calibration of the model.** To ensure the adequacy of the obtained results, the model was tested. At the calibration stage, the mode of normal operation of the network without SPPs was calculated. The obtained values of voltages in nodes, currents in lines and power losses were compared with the actual operating data of the corresponding distribution network under normal operating conditions. The discrepancies were minimal ( $\sim 2\%$ ), which confirmed the correctness of the given network parameters.

A comparison of the measured and simulated voltage values is given in Fig. 6 and in Table 1. The analysis of the results shows that at night and in the morning hours, the

deviation of the model from the actual data is minimal and does not exceed  $0.2\%$ , which indicates the high accuracy of the reproduction of modes under low loads and the absence of SPPs generation.

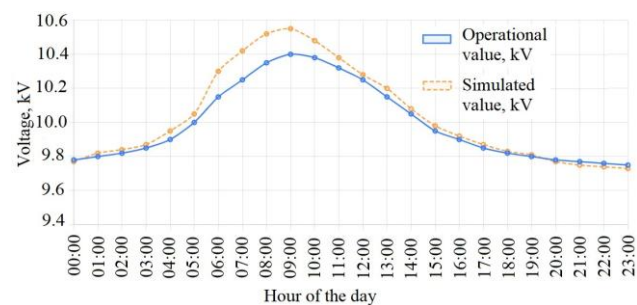


Figure 6 – Graphs of measured and simulated voltage values in the control node

During the daytime period, especially in the interval from 10:00 to 14:00, there is a maximum difference between the measured and calculated voltage values, which reaches  $1.5\text{--}2\%$ .

This is explained by the influence of solar generation, which is characterized by high dynamics of changes, as well as simplifications in the mathematical model (linear characteristics of elements, averaging of the insolation profile, etc.). In the evening, the error gradually decreases and stabilizes at around  $0.5\%$ , which is again consistent with practical observations.

Thus, the mathematical model built in SICAD is a tool that reflects with sufficient accuracy the behavior of a real  $10\text{ kV}$  distribution network with an integrated SPP. It takes into account key factors: generation-consumption ratio, line parameters, variability of SPP generation and inverter functionality.

The presence of such a model created the basis for conducting a comprehensive analysis of standard and emergency modes of operation of the system.

Table 1 – Comparison of measured and simulated node voltage values

Time	Operational value, kV	Simulated value, kV	Error, %
00:00	9.78	9.77	-0.10
01:00	9.80	9.82	0.20
02:00	9.82	9.84	0.20
03:00	9.85	9.87	0.20
04:00	9.90	9.95	0.51
05:00	10.00	10.05	0.50
06:00	10.15	10.30	1.48
07:00	10.25	10.42	1.66
08:00	10.35	10.52	1.64
09:00	10.40	10.55	1.44
10:00	10.38	10.48	0.96
11:00	10.32	10.38	0.58
12:00	10.25	10.28	0.29
13:00	10.15	10.20	0.49
14:00	10.05	10.08	0.30
15:00	9.95	9.98	0.30
16:00	9.90	9.92	0.20
17:00	9.85	9.87	0.20
18:00	9.82	9.83	0.10
19:00	9.80	9.81	0.10
20:00	9.78	9.77	-0.10
21:00	9.77	9.75	-0.20
22:00	9.76	9.74	-0.20
23:00	9.75	9.73	-0.21

**Analysis of the operating modes of a 10 kV distribution network with an integrated SPP.** On the basis of the developed and validated mathematical model, a comprehensive analysis of the standard and emergency modes of operation of the 10 kV distribution network with an integrated SPP with a capacity of 5 MW was carried out. The purpose of the analysis was to quantify the impact of SPPs generation on key system parameters such as voltage levels, current distribution, power loss, and to identify potential safety and reliability issues.

The analysis of normal mode of operation was carried out for various combinations of consumer load and generation from SPP during characteristic daily cycles. Two characteristic scenarios were considered:

1. Winter evening maximum consumption mode.
2. Mode of the summer maximum of energy generation by power plants.

The SPP has the most significant effect on the voltage distribution along the feeder. As can be seen from the simulation results presented in Fig. 7, in the night minimum mode (without SPP) there is a classic profile with a smooth voltage reduction from the substation (node №0 – 10.5 kV) to the end consumers (node №10 – 10.15 kV).

During the daytime period, when the generation of SPPs reaches maximum values and consumption remains relatively high, at the point of connection of the station (node №7) there is a noticeable increase in the voltage level (curve 3). In this mode, the voltage value approaches the upper limit of the permissible range, which can lead to a violation of the requirements for voltage regulation in distribution networks and create an additional load on the electrical equipment of consumers.

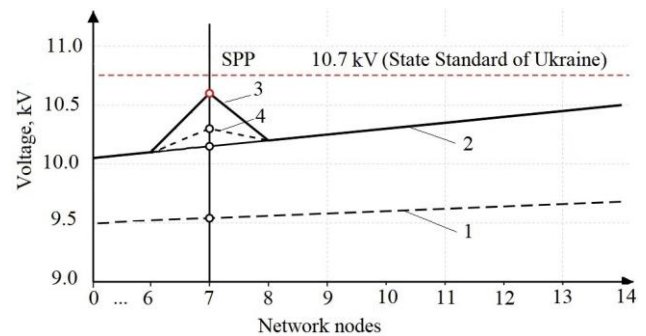


Figure 7 – Voltage profile along the feeder of 10 kV for different modes of network operation in the summer:

- 1 – mode of night minimum load (without SPP generation);
- 2 – daytime load mode without SES generation;
- 3 – day mode with maximum SPP generation (without reactive power regulation);
- 4 – day mode with maximum SPP generation (with reactive power regulation)

The increase in voltage is explained by the injection of active power from the SPP into the distribution network, which leads to a decrease in the current coming from the substation and to a change in the distribution of power flows along the feeder. With a significant share of local generation, this can cause a voltage rise effect, especially in nodes located near the connection point of the generation source. Activation of the reactive power control function of the SPP inverter (curve 4) allows you to effectively compensate for this voltage increase due to the consumption of reactive power from the network and maintain the voltage level within the permissible regulatory values.

The effect of SPP on voltage losses is nonlinear and strongly depends on the ratio of generation and consumption. The results of the calculations are presented in Fig. 7. As can be seen from the table, during the daytime peak of consumption, losses without SPP increase significantly due to an increase in load currents.

Connecting the SPP allows you to significantly reduce these losses (by almost 40 %), since the station provides local coverage of the load, reducing the currents flowing from the substation. However, in a scenario with overgeneration (for example, on a day off when consumption is low and generation is high), it is possible to increase losses on certain sections of the network due to reverse power flows.

The simulation confirmed the phenomenon of reverse power flows. During daytime hours, when the generation of SPPs exceeds the consumption in the L17 section, the excess electricity starts to flow to the higher sections of the network and to the 10/0.4 kV buses of the substation.

This leads to a change in the direction of the current in these areas. Although this phenomenon is expected, it requires verification of relay protection and automation settings designed for unidirectional flows.

Two key emergency scenarios were simulated to assess the stability of the system:

- disconnection of SPP at the peak moment of generation;
- short-term locking on one of the lines supplying the feeder.

Summer maximum power generation by power plants

Voltage drop dU						
Nº	Line ID	Nº of pole for the most distant connection	Voltage drop dU, %	Voltage drop dU, V	Voltage level, V	Deviation from the rated voltage, %
1	L18	37	0.1	0.22	219.17	-0.38
2	L17	36	0.12	0.26	219.13	-0.4
3	L16	35	0.12	0.26	219.13	-0.4
4	L15	34	0.07	0.15	219.24	-0.35
5	L14	33	-0.25	-0.55	219.94	-0.03
6	L13	32	-1.6	-3.51	222.9	1.32
7	L12	31	-0.24	-0.53	219.92	-0.04
8	L11	30	-0.19	-0.42	219.81	-0.09
9	L9	28	-0.09	-0.2	219.59	-0.19
10	L8	27	0.04	0.09	219.3	-0.32
11	L7	26	0.06	0.13	219.26	-0.34

a

Winter evening maximum consumption mode

Voltage drop dU						
Nº	Line ID	Nº of pole for the most distant connection	Voltage drop dU, %	Voltage drop dU, V	Voltage level, V	Deviation from the rated voltage, %
1	L18	37	0.49	1.08	218.31	-0.77
2	L17	36	0.88	1.93	217.46	-1.15
3	L16	35	1.07	2.35	217.04	-1.35
4	L15	34	1.2	2.63	216.76	-1.47
5	L14	33	2.06	4.52	214.87	-2.33
6	L13	32	2.5	5.48	213.91	-2.77
7	L12	31	2.62	5.75	213.64	-2.89
8	L11	30	2.79	6.12	213.27	-3.06
9	L9	28	3.06	6.71	212.68	-3.33
10	L8	27	3.44	7.55	211.84	-3.71
11	L7	26	3.51	7.7	211.69	-3.78

b

Figure 7 – 10/0.4 kV feeder voltage losses for the summer maximum mode of SPP energy generation and in the winter evening maximum mode of consumption

A sudden shutdown of a SPP with a capacity of 5 MW during the period of maximum generation leads to an instant shortage of power in the local area of the network. This causes a sharp voltage drop at the connection point (L13) – to 2.5 %, as shown in Fig. 7. Such a voltage fluctuation can lead to incorrect operation of sensitive consumer equipment. Simulations have shown the need for fast-acting sources of compensation (such as energy storage systems or other generating capacity) to maintain stability in similar situations (Fig. 8).

Short-circuit modeling confirmed the correct operation of standard protections. The SPP inverter protection system ensured a quick disconnection of the station from the network in the event of an accident, which prevents feeding of the damage point. After eliminating the short circuit and restoring the voltage, the inverter model, which meets modern requirements, demonstrated the

possibility of automatic re-engagement with the required time delay.

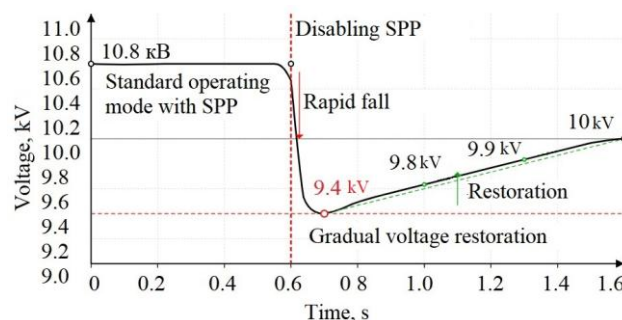


Figure 8 – Dynamics of voltage change in node №7 during sudden shutdown of the SPP (t = 0.6 s)

Based on the analysis, the following practical recommendations were formulated for operators of distribution systems and project organizations:

1. Mandatory use of reactive power regulation mode ( $Q(U)$ ) by modern SPP inverters. This is the most effective way to prevent overvoltages at the connection point without the use of additional expensive equipment.

2. When planning new SPPs, it is necessary to carry out detailed modeling not only of regular but also of emergency modes to assess the impact on the quality of electricity and the stability of the network, especially when connecting high-power stations to weak networks.

3. Consideration of the possibility of installing energy storage systems in places of concentration of solar generation. Energy storage systems will allow you to smooth out the generation schedule, accumulating excess energy during the day and giving it away in the evening, as well as provide quick compensation in case of sudden shutdowns of the SPP.

4. Adaptation of relay protection schemes taking into account the possibility of reverse power flows and the peculiarities of the behavior of inverters in case of accidents.

Thus, the simulations carried out in the SICAD software complex clearly demonstrated both the positive and potentially negative impact of solar generation on the 10/0.4 kV network operation modes. Positive effects should include reducing power losses and maintaining voltage during peak hours. The main problems are the risk of overvoltage in the mode of excessive generation and voltage fluctuations during sudden changes in the modes of operation of the SPP. The proposed technical solutions, such as the use of inverter control functions, allow to effectively minimize these risks and ensure stable and reliable operation of the power system with a high share of renewable energy sources.

**Discussion of research results.** The obtained simulation results in the SICAD software environment confirm that connecting the SPP to a 10 kV network significantly affects its operating modes. Attention is drawn first of all to the appearance of reverse power flows (Fig. 6, curve 2), which is explained by the excess of generation over local consumption according to balance dependence (1). This phenomenon fundamentally changes the architecture of distribution networks, which traditionally functioned according to the «source–consumer» scheme.

Analysis of voltage losses showed that in the case of SPP operation during the daytime period, losses decrease from 0.88 % to 0.12 % (Fig. 7, L17), which is quantitatively confirmed by the ratio (2). The decrease in losses is explained by the decrease in currents in the branch «substation – node with SPP», since part of the load is covered locally. At the same time, when generation exceeds consumption in adjacent areas of the network, an increase in losses is possible, which indicates an ambiguous effect of SPP integration.

The most critical result is the appearance of overvoltages in the connection node (Fig. 6, curve 3), which is explained by dependence (3): with low consumption and significant generation, the voltage in the node №7 exceeds the permissible level. This creates a threat of violation of regulatory modes of operation. At the

same time, the application of inverter regulation of reactive power according to algorithm (5) made it possible to keep the voltage within the normative limits (Fig. 6, curve 4).

The proposed solution therefore provides effective overvoltage compensation without the need to install additional equipment.

Compared to known works, where SPP are considered exclusively as sources of active power without taking into account the regulatory properties of inverters, the obtained result shows a significant advantage. In contrast to the [6] approaches, where the installation of additional compensating devices is proposed, it is shown in the present study that by using  $Q(U)$  – the adjustment of the inverters (Figure 6, curve 4) can stabilize the voltage without significant additional investment. This becomes possible thanks to the features of modern inverters, which combine the functions of energy conversion and regulation of network modes.

The simulation of emergency modes confirmed that when the SPP is suddenly disconnected, there is a sharp voltage drop of up to 9.4 kV (Fig. 7). This is explained by the instantaneous lack of power in the local part of the network. The identified effect indicates the need to use fast-acting backup sources or energy storage systems to ensure smooth modes. Thus, the study confirms the relevance of using hybrid solutions «SPP – energy storage» to increase the reliability of the network.

The results of the work allow us to conclude that the identified problems – of reverse power flows, overvoltages and voltage fluctuations – have been confirmed and partially solved. In particular, losses were reduced thanks to local balancing (Fig. 7), overvoltages – thanks to inverter regulation (Fig. 6, curve 4), and the impact of emergency modes – was partially minimized thanks to the promising use of energy storage devices (Fig. 8).

At the same time, it is necessary to note the limitations of the study. First, the use of averaged insolation profiles and simplified equipment models has conditioned deviations between the estimated and operational voltage values Table 1, reaching 1.5–2 %. Secondly, the work does not take into account the influence of harmonic components and flickers, which are significant factors for assessing the quality of electricity. Thirdly, only typical emergency scenarios are considered, while more complex combinations are possible in real operation.

Disadvantages include the lack of analysis of the mass connection of several SPPs in one feeder, as well as insufficient consideration of the impact on relay protection, which may not work correctly in cases of reverse power flows.

Further development of the research should be focused on three areas: firstly, on modeling the integration of energy storage systems, which will allow smoothing generation profiles and ensure reliability in case of accidents; secondly, on taking into account harmonic distortions and issues of electromagnetic compatibility, which determines the quality of energy; thirdly, on the development of adaptive relay protection algorithms for decentralized generation conditions.

It is these directions that will ensure practical suitability and expand the limits of application of the obtained results.

**Conclusions.** As a result of the simulation of the power flows in the 10/0.4 kV network with the SPP connected, it is established that there are return flows in the daytime period when generation exceeds consumption Figure 6, curve 2. This allows us to explain the change of the classical architecture «source–consumer» to a decentralized structure with two-way energy movement. A distinctive feature of the result is the possibility of quantifying such flows (up to 1.2 MW in the hours of maximum insolation), which confirms their significance for the modes of operation of the network.

The analysis of electricity losses showed their decrease during the day from 0.88 % to 0.12 % (L17) due to the local coverage of the SPP load. This indicates an increase in the energy efficiency of the network in the presence of generation. The difference from the known results lies in taking into account not only average, but also local losses in different parts of the network, which made it possible to detect their possible increase in cases of excess generation. Thus, the result is explained by the change in the direction of currents in the branches of the network and their uneven distribution.

A voltage deviation in the SPP connection node (L17) was detected, where the voltage exceeds the standard level by 0.76 %. This is explained by low local consumption with significant generation. Unlike existing approaches, where overvoltages are proposed to be compensated by additional devices, the obtained results showed that the application of inverter regulation of reactive power ensures that the voltage is kept within the normal range without additional investment. The advantage of the solution is to use the standard capabilities of the inverter, which makes it more economically feasible.

Modeling of emergency modes showed that with a sudden shutdown of the SPP, there is a sharp voltage drop to 9.4 kV, which is explained by an instantaneous power shortage. This allows us to conclude that it is necessary to integrate fast-acting energy storage systems. Unlike known studies, where similar effects were not considered, this work obtained a quantitative assessment of the voltage change during an emergency shutdown. The advantage of the result is its applied nature, which allows taking into account dynamic risks when designing networks.

It should therefore be noted that the integration of SPPs into 10/0.4 kV grids, despite a number of challenges, has demonstrated substantial potential for improving energy efficiency and reliability of power supply. The proposed approaches to loss reduction, voltage stabilization and compensation of emergency modes using inverter regulation and energy storage systems provide competitive advantages compared to known solutions and create the basis for the further development of intelligent distribution networks.

## References

1. SiCAD powerline designing. [Online]. Available: <https://app.sicad.org/>
2. Y. Elomari, M. Norouzi, M. Marin-Genescà, A. Fernández, and D. Boer, "Integration of solar photovoltaic systems into power networks: A scientific evolution analysis," *Sustainability*, vol. 14, no. 15, Jul. 2022, Art. no. 9249, doi: <https://doi.org/10.3390/su14159249>
3. I. B. Majeed and N. I. Nwulu, "Impact of reverse power flow on distributed transformers in a solar-photovoltaic-integrated low-voltage network," *Energies*, vol. 15, no. 23, Dec. 2022, Art. no. 9238, doi: <https://doi.org/10.3390/en15239238>
4. P. Budanov, I. Kyrysov, K. Brovko, D. Rudenko, P. Vasiuchenko, and A. Nosyk, "Development of a solar element model using the method of fractal geometry theory," *Eastern-European Journal of Enterprise Technologies*, vol. 3, no. 8(111), pp. 75–89, Jun. 2021, doi: <https://doi.org/10.15587/1729-4061.2021.235882>
5. I. B. Majeed and N. I. Nwulu, "Reverse power flow due to solar photovoltaic in the low voltage network," *IEEE Access*, vol. 11, pp. 44741–44758, 2023, doi: <https://doi.org/10.1109/access.2023.3273483>
6. M. Mahdavi, H. H. Alhelou, N. D. Hatzargyriou, and F. Jurado, "Reconfiguration of electric power distribution systems: Comprehensive review and classification," *IEEE Access*, vol. 9, pp. 118502–118527, 2021, doi: <https://doi.org/10.1109/ACCESS.2021.3107475>
7. D. Almeida, J. Pasupuleti, and J. Ekanayake, "Comparison of reactive power control techniques for solar PV inverters to mitigate voltage rise in low-voltage grids," *Electronics*, vol. 10, no. 13, Jun. 2021, Art. no. 1569, doi: <https://doi.org/10.3390/electronics10131569>
8. L. Yao, Y. Wang, and X. Xiao, "Concentrated solar power plant modeling for power system studies," *IEEE Transactions on Power Systems*, vol. 39, no. 2, pp. 4252–4263, Mar. 2024, doi: <https://doi.org/10.1109/TPWRS.2023.3301996>
9. I. Frimannslund, T. Thiis, A. Aalberg, and B. Thorud, "Polar solar power plants – Investigating the potential and the design challenges," *Solar Energy*, vol. 224, pp. 35–42, Aug. 2021, doi: <https://doi.org/10.1016/j.solener.2021.05.069>
10. N. Shorabeh, N. N. Samany, F. Minaei, H. K. Firozjaei, M. Homaei, and A. D. Boloorani, "A decision model based on decision tree and particle swarm optimization algorithms to identify optimal locations for solar power plants construction in Iran," *Renewable Energy*, vol. 187, pp. 56–67, Mar. 2022, doi: <https://doi.org/10.1016/j.renene.2022.01.011>
11. M. E. Abdeselem, T. E. Boukeli, and M. S. Mecibah, "Comparative analysis of integrating different power cycles into a concentrated solar power plant," *Solar Energy Materials and Solar Cells*, vol. 285, Jun. 2025, Art. no. 113534, doi: <https://doi.org/10.1016/j.solmat.2025.113534>
12. T. E. K. Zidane *et al.*, "Grid-connected Solar PV power plants optimization: A review," *IEEE Access*, vol. 11, pp. 79588–79608, Jul. 2023, doi: <https://doi.org/10.1109/access.2023.3299815>
13. X. Li *et al.*, "Operation optimization of electrical-heating integrated energy system based on concentrating solar power plant hybridized with combined heat and power plant," *Journal of Cleaner Production*, vol. 289, Mar. 2021, Art. no. 125712, doi: <https://doi.org/10.1016/j.jclepro.2020.125712>
14. Q. Wang, G. Pei, and H. Yang, "Techno-economic assessment of performance-enhanced parabolic trough receiver in concentrated solar power plants," *Renewable Energy*, vol. 167, pp. 629–643, Nov. 2020, doi: <https://doi.org/10.1016/j.renene.2020.11.132>
15. H. Ami Ahmadi, N. Variji, A. Kaabinejadian, M. Moghimi, and M. Siavashi, "Optimal design and sensitivity analysis of energy storage for concentrated solar power plants using phase change material by gradient metal foams," *Journal of Energy Storage*, vol. 35, Mar. 2021, Art. no. 102233, doi: <https://doi.org/10.1016/j.est.2021.102233>
16. F. Wang, Y. Gao, Z. Chen, X. Gong, D. Zhu, and W. Cong, "A path planning algorithm of inspection robots for solar power plants based on improved RRT\*," *Electronics*, vol. 12, no. 21, Oct. 2023, Art. no. 4455, doi: <https://doi.org/10.3390/electronics12214455>

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### **МОДЕЛЮВАННЯ ІНТЕГРАЦІЇ СОНЯЧНОЇ ЕЛЕКТРОСТАНЦІЇ В РОЗПОДІЛЬЧУ МЕРЕЖУ 10/0.4 КВ ІЗ ВИКОРИСТАННЯМ ПЛАТФОРМИ SICAD**

Інтенсивний розвиток відновлюваної енергетики в Україні та світі зумовлює потребу у глибокому дослідженні процесів інтеграції сонячних електростанцій у розподільчі мережі середньої напруги. Збільшення частки децентралізованих джерел генерації змінює установлені режими роботи електричних систем, ускладнює балансування активної та реактивної потужності, впливає на рівень напруги у вузлах і створює додаткові вимоги до систем захисту та автоматики. Актуальність проблеми підсилюється тим, що мережі класу напруги 6–10 кВ спочатку проєктувалися для роботи у традиційному напрямку потоків потужності – від підстанції до споживачів, тоді як підключення сонячних станцій спричиняє появу зворотних потоків і нерівномірний розподіл навантаження. Метою даного дослідження є моделювання впливу фотоелектричних станцій на роботу розподільчих мереж та аналіз можливостей інверторів у підвищенні ефективності регулювання напруги й підтримки надійності електропостачання. Об'єктом дослідження є розподільча мережа 10/0.4 кВ з інтегрованою сонячною електростанцією потужністю 5 МВт, що відтворює типовий приклад сучасної системи з відновлюваними джерелами. Основна гіпотеза полягає в тому, що використання інверторів з алгоритмом регулювання реактивної потужності забезпечує стабільність режимів роботи та знижує негативні наслідки коливань сонячної генерації. У роботі застосовано комплексний підхід, що включає аналітичні методи розрахунку потужності та комп'ютерне моделювання у програмному середовищі SICAD. Це дозволило відтворити роботу мережі у різних сценаріях: при нічному мінімумі навантаження, денному піку генерації, а також у перехідних режимах. Додатково досліджувались аварійні ситуації, серед яких раптове відключення сонячної електростанції та виникнення коротких замикань. Такий підхід дає можливість оцінити не лише штатні, але й аварійні умови функціонування системи. Наукова новизна роботи полягає у розробленні підходу до оцінювання впливу фотоелектричних електростанцій на режими роботи розподільчих електричних мереж середньої напруги з урахуванням можливостей керування реактивною потужністю інверторів та змінного характеру сонячної генерації. Практична значущість результатів полягає у можливості їх використання для розробки методичних рекомендацій щодо інтеграції фотоелектричних станцій у мережі середньої напруги, а також для вдосконалення алгоритмів регулювання інверторів. Отримані висновки можуть бути корисними як операторам систем розподілу, так і проєктним організаціям при плануванні розвитку електричних мереж з урахуванням зростання частки відновлюваних джерел енергії.

**Ключові слова:** розподільча електрична мережа; сонячна електростанція; фотоелектрична генерація; інвертор; регулювання напруги; реактивна потужність; комп'ютерне моделювання.