



Distributed generation for continuous power supply of urban areas

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Abstract. The work aims to study the potential for efficient use of distributed generation in the small urban power supply system and its feasibility in modern urban microgrids. The work used statistical data analysis, mathematical simulation using the PSCAD software suite, and simulations of a distributed generation facility based on a battery-type electrical energy storage and photovoltaic plant. The mains network of the facility located in the small residential estate of Tashkent, Republic of Uzbekistan is accepted as the object of the study. The results calculated using an urban grid simulation model showed that the use of various distributed generation sources improves the reliability of power supply and reduces the burden on medium- and high-voltage electrical networks. Moreover, this activity in the shown example improves load balancing in low-voltage networks: power loss in network cells and voltage drop were reduced by 5 and 3%, respectively. Thus, the use of distributed generation in the urban power supply system was scientifically justified using the example of a real microgrid located in Kokand. A detailed mathematical analysis of the technical and economic indicators of the urban electrical supply system was performed to formulate the comprehensive model of the system state. In parallel, a simulation model was developed based on detailed models to reflect the layout of the considered electrical network and dynamics of the distributed generation facility. Further research will include the feasibility study of direct current microgrids for urban power supply, taking into account the active introduction of renewable energy sources.

Keywords: power supply system, distributed generation, photovoltaic panels, energy storage system, transformer substation, electrical energy losses, electrical load graph, technical-economic indicator, imitation model

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ЭНЕРГЕТИКА

Научная статья

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Использование распределённой генерации для обеспечения непрерывного электроснабжения в городских районах

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Резюме. Цель – изучение потенциала эффективного использования распределенной генерации в системе электроснабжения малого городского района и научное обоснование ее применения в рамках современных микросетей городов. В работе были использованы статистический анализ данных, математическое моделирование с использованием программного комплекса PSCAD и имитационное моделирование объекта распределенной генерации на основе накопителя электрической энергии аккумуляторного типа и фотоэлектрической установки. В качестве объекта исследования принята электрическая сеть объекта, расположенного в небольшом микрорайоне города Коканд, Республика Узбекистан. Расчетные результаты, полученные на основе разработанной имитационной модели городской электрической сети, показывают, что использование различных источников распределенной генерации повышает надежность электроснабжения и снижает нагрузку на электрические сети среднего и высокого напряжения. Кроме того, данное мероприятие в представленном примере способствует выравниванию графика нагрузки в сетях низкого напряжения: снизило потери электроэнергии в сетевых элементах на 5%, а также на 2,9% уменьшило уровень падения напряжения. Таким образом, выполнено научное обоснование использования распределенной генерации в городской системе электроснабжения на примере реальной микросети, расположенной в городе Коканд. Выполнен подробный математический анализ технико-экономических показателей системы электроснабжения города, в результате чего была сформулирована

на комплексная модель состояния системы. Параллельно разработана имитационная модель с использованием детальных моделей, отражающая конфигурацию рассматриваемой электрической сети и динамику работы объекта распределенной генерации. Дальнейшие исследования будут направлены на технико-экономическое обоснование применимости микросетей на постоянном токе для электроснабжения городов с учетом активного внедрения возобновляемых источников энергии.

Ключевые слова: система электроснабжения, распределенная генерация, солнечные панели, система хранения энергии, трансформаторная подстанция, потери электрической энергии, график нагрузки, технико-экономический показатель, имитационная модель

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INTRODUCTION

Currently, ensuring the high-quality, reliable, and uninterrupted supply of electrical energy that fully meets regulatory requirements has become a globally pressing issue due to the expansion and development of city areas, the formation of new infrastructure, and the increasing number and diversity of electrical consumers. In both developed and developing countries, measures taken to generate, transmit, and distribute electrical energy while preserving the environment are proving to be effective. Given the high population density and electrical load concentration in city areas, planned efforts to reduce environmental impact are essential^{4,7} [1, 2].

The continuous power supply in city areas can be achieved by maintaining the normal operating conditions of local electrical grids through the integration of distributed generation. Distributed generation sources can be integrated into low voltage (0,4 kV) and medium voltage (10 kV) electrical grids. In many city areas, the excessive loading and aging of low voltage local electrical grids lead to additional energy losses and an increased number of faults. Considering this, it is advisable to utilize distributed generation sources, such as photovoltaic solar power stations and energy storage systems, in proximity to electricity consumers in low voltage grids⁴ [1, 3–19].

As a result, the integration of distributed generation in cities represents a promising direction for the development of the power sector and helps to mitigate the challenges associated with the intensive growth of electrical loads, which is particularly relevant for city areas. This approach also enables a reduction in electricity flow through transmission and distribution networks operating at 10 kV, 35 kV, and 220 kV voltage levels^{5,7,8} [7–24].

It should be noted that the utilization of distributed generation contributes to reducing the technical and economic costs associated with upgrading and replacing local power generation sources and transmission lines, as well as transformer substations (TS) and cable lines in city areas that were installed 40–50 years ago. Moreover, due to the high population density and the compact layout of buildings, modernizing and replacing city electrical networks is a complex and challenging task^{5,6} [7, 10]. In this article, the sequential process of developing a comprehensive system for the integration of distributed generation sources, specifically photovoltaic solar power stations and energy storage systems, into local electrical grids is examined. This approach is based on promising plans for the development of Uzbekistan's energy sector and aims to enhance the technical and economic efficiency of low voltage electrical grids. The study focuses on

⁴On measures to improve the effectiveness of reforms aimed at transitioning the Republic of Uzbekistan to a “green” economy by 2030: Resolution of the President of the Republic of Uzbekistan of 2 December, 2022 No. PP-436./ О мерах по повышению эффективности реформ, направленных на переход Республики Узбекистан на «зеленую» экономику до 2030 года: Постановление Президента Республики Узбекистан от 02.12.2022 г. № ПП-436.

⁵Concept for providing the Republic of Uzbekistan with electricity for 2020-2030. Access mode: <uz-concept-energo-2020.pdf> (date accessed: 15 September 2025). / Available from: <uz-concept-energo-2020.pdf> [Accessed 15th September 2025]. / Концепция обеспечения Республики Узбекистан электрической энергией на 2020-2030 годы. Режим доступа: <uz-concept-energo-2020.pdf> (дата обращения: 15.09.2025).

⁶Development strategy for electric distribution networks of the Republic of Uzbekistan until 2025. / Available from: https://www.het.uz/uploads/e2dff98e-6eb9-2c89-3ff6-2bc23943bbe7_media_.pdf [Accessed 15th September 2025]. / Стратегия развития распределительных электрических сетей Республики Узбекистан до 2025 года. Режим доступа: https://www.het.uz/uploads/e2dff98e-6eb9-2c89-3ff6-2bc23943bbe7_media_.pdf (дата обращения: 15.09.2025).

constructing technical and economic models for these systems and optimizing the parameters of electrical networks through a unified model. The PSCAD (Power Systems Computer Aided Design) 4.6 simulation software was utilized due to its extensive component library, ease of electrical circuit design, and the ability to efficiently generate and analyze output waveforms. For a real application, a systematic approach was employed to determine and compare key influence parameters, ensuring improved energy efficiency and reliability of power supply.

OBJECTS AND RESEARCH METHODS

The research object is the electrical grids of the city power supply system. To implement and integrate distributed generation sources within city areas, it is essential to comprehensively examine and analyze their types⁵ [11, 17].

Types of distributed generation technology:

1. Renewable energy technologies include:

- fuel cells;
- solar photovoltaic;
- Wind & Wave Energy;
- hydro electric energy.

2. Commercial energy technologies include:

- IC engines;
- gas turbines;
- micro turbines;
- energy storage technologies.

The integration of distributed generation into the city's power supply system can have a significant impact, affecting factors such as voltage regulation, power flow, reliability, and more. Installing distributed generation changes the traditional characteristics of the distribution system, which is typically designed for unidirectional power flow. With the addition of distributed generation, an extra power source is introduced. If its capacity exceeds consumer demand, the power flow reverses. At a certain point between the substation and the distributed generation, the actual power flow becomes zero, as excess power flows back into the system⁵ [4, 11, 20].

Rules have been developed to manage reverse power flow, reduce losses by determining the optimal location of distributed generation, and assess the impact of distributed generation on overload protection systems. The modeling of the impact of distributed generation and the analysis of the zero point have been outlined in current scientific literature. The IEC 61727 standard series, consisting of six parts, provides the criteria and requirements for connecting distributed generation sources to the power supply system. These standards set the benchmarks for integrating distributed generation into electrical power systems. The effects of distributed generation installations on voltage, losses, and the reliability indices of residential distribution networks are studied based on various criteria⁵ [2, 5, 10, 23].

The research object is the residential and public buildings in a small microdistrict of Kokand city. Initially, the condition of the existing electrical networks in the area was analyzed. The following indicators of these electrical networks were obtained:

- the existing electrical load and load density of the area;
- the electrical energy losses in the networks;
- the annual loading condition of the transformer substations;
- voltage loss and variation in the electrical networks;
- the number of interruptions occurring in the power supply system.

Based on the conducted research, collected statistical data, and measurement results, the following real situation was observed. The object of the study includes 10/0,4 kV transformer substations and 0,4 kV cable lines. The layout diagram of this object is provided in Fig. 1, presenting the full structure. Through this diagram, the addresses, brands, and parameters of the electrical networks at four research points can be obtained. Based on the provided geodetic data, this diagram has been developed, and the value indicators are pre-

⁵Electrical installation rules (EIR). All current sections of EIR-6 and EIR-7. / Available from: <https://en-res.ru/wp-content/uploads/2020/02/pue.pdf?ysclid=mktzwurn5u530900880> [Accessed 15th September 2025]. / Правила устройства электрических установок. Все действующие разделы ПУЭ-6 и ПУЭ-7. Режим доступа: <https://en-res.ru/wp-content/uploads/2020/02/pue.pdf?ysclid=mktzwurn5u530900880> (дата обращения: 15.09.2025).

⁸Renewable power generation costs in 2022. Available from: <https://cdssolar.com/renewable-power-generation-costs-in-2022/> [Accessed 18th September 2025]. / Затраты на производство возобновляемой электроэнергии в 2022 году. Режим доступа: <https://cdssolar.com/renewable-power-generation-costs-in-2022/> (дата обращения: 15.09.2025).

sented in tabular form ("Regional Electric Networks" JSC, Uzbekistan, 2024). The object of this study is a real case based on a small microdistrict located in Kokand, Republic of Uzbekistan. The theoretical scientific approach developed in this research aims to enhance the energy efficiency of the system^{4,6}.

The primary objective of the authors' research is to ensure the reliability and continuity of the power supply for buildings and structures within the city electrical grid. In this regard, the study considers medium voltage power distribution through two main transmission schemes utilizing domestically manufactured АПвПуГ (AXRh) cables (it is a power cable with aluminum conductors, XLPE insulation, reinforced polyethylene outer sheath, without an armored protective layer), while low voltage networks employ АББг (APPu) aluminum conductor cables (it is a power cable with aluminum conductors, PVC insulation, PVC outer sheath, and without an armored protective layer). Additionally, oil filled TM type power transformers have been selected for integration into the comprehensive transformer substation to optimize the overall system performance⁶ [1].

For TS No. 421 (160 kVA), 6 buildings are connected; for TS No. 419 (100 kVA), 4 buildings are connected; for TS No. 420 (100 kVA), 2 buildings are connected; and for TS No. 422 (160 kVA), 5 buildings are connected. The parameters of the transformer substations and connection lines for these buildings were obtained from the local electrical network enterprise.

The values of the performance indicators for the electrical networks in the area were calculated based on the current situation. The results of these calculations are presented in Table 1. The overall analysis indicators of the principle diagram are included in the table for the aforementioned object.

Through the analysis of the condition of local electrical networks in the reviewed scenario, the need for the implementation of distributed generation sources in this system is substantiated. Integration is achieved through the construction of a simulation model for the electrical grid of this power supply system [6, 10, 14].

These indicators are considered the key factors influencing energy efficiency and the reliability of the power supply. Since numerous modern foreign studies have already analyzed these aspects, a detailed examination of each factor is not provided in this research [12, 17–19].

In the city area, the electrical load density in the transformer substations and the low voltage cable lines coming from them is taken as the main indicator. In this case, the electrical load density is calculated based on the specified area, where the active load (MW) corresponding to 1 km² of the area is determined. Based on the research and measurement results conducted at the site, it is observed that due to the aging of lines and transformer substations in the area, as well as the variable seasonal nature of the electrical load of energy consumers, the losses and various interruption conditions in the electrical networks are significantly high. For the low voltage object, the use of distributed generation systems,

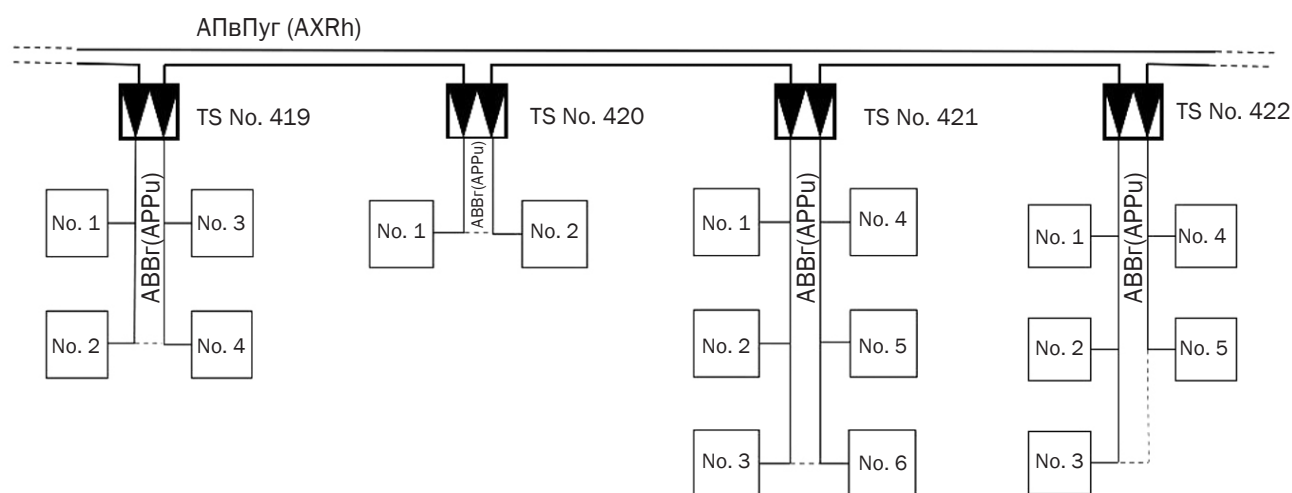


Fig. 1. The layout diagram of the electrical networks of the object located in a small microdistrict of Kokand city

Рис. 1. Схема расположения электрических сетей объекта, расположенного в небольшом микрорайоне города Коканда

Table 1. Collected statistical data of the electrical networks located in the small microdistrict of Kokand city, 2024
Таблица 1. Собранные статистические данные по электрическим сетям, расположенным в небольшом микрорайоне города Коканд 2024 г.

No.	The address of the electrical networks (transformer substations and cable line complexes)	Electrical load density, MW/km ²	The annual share of losses in the transformer substations and outgoing lines, %	Annual overload in the electrical networks, hours	Voltage loss in the electrical networks, %	The annual number of interruptions occurring in the power supply system
1	TS No. 419	2	10,5	4400	5	27
2	TS No. 420	1.6	8	3400	4	12
3	TS No. 421	3	12	5100	5.5	36
4	TS No. 422	2.2	11,4	4900	5.2	32

such as solar panels and energy storage systems, as well as their management systems in operational conditions, is considered. Currently, based on global statistical data, it can be seen that the economic costs of solar panels and energy storage systems are decreasing year by year. This justifies the payback period for these systems. Technically, their advantages require the development of advanced parameters and control systems [9, 15, 16].

For the reviewed object, the following issues are addressed by applying distributed generation in the city area: optimizing the electrical load profiles, constructing a mathematical model of the electrical network considering its technical-economic indicators, and forming an automatic control system. Optimization, mathematical modeling, and control methods are used to solve these problems. Initially, suitable distributed generation models are selected for the given object. In Fig. 2, we consider the model constructed for the integrated use of solar panels and energy storage systems. In this study, the use of a Deye brand inverter has been considered in the model, taking into account the current conditions in Uzbekistan^{4,5}.

The key components, as mentioned earlier, include medium voltage cable lines, a 10/0,4 kV transformer substation, and low voltage cable lines in the city area. The total cost of solar photovoltaic stations and energy storage systems has been decreasing year by year. According to international statistical data, it is expected that by 2030, the cost will decrease by more than 30%. The main components used in these systems are illustrated in Fig. 2. A distributed generation source control system has been developed, with control primarily based on power extraction from the solar photovoltaic station, charging, and discharging energy storage systems^{5,6} [14].

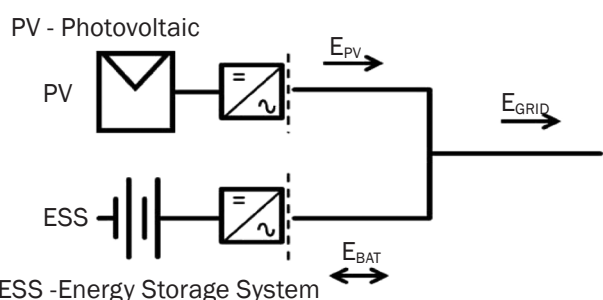


Fig. 2. Overall photovoltaic (PV) battery system connected to equivalent voltage source: ESS – energy storage system, BAT – battery

Рис. 2. Комплексная система солнечных панелей и аккумуляторов, подключенная к эквивалентному источнику напряжения: ESS – система накопления энергии, BAT – батарея

The operation of these two types of distributed generation sources shown in Fig. 2 is interdependent. The operation mode of the solar photovoltaic station and the energy storage system complement each other. In developed countries, the experience of complex use of these two systems has proven effective by regulating electrical energy tariffs. In global practice, the tariff formation system is applied by dividing the daily period into 3 and 5 parts. For the lowest, i.e., cheapest tariff period, energy storage systems are charged by taking power from the electrical grid. During the highest price period, i.e., when the tariff increases, electricity is returned to the grid, generating profit. This approach allows energy storage systems to recover part of their operating time and cover their costs over the years [12, 13, 19].

As shown in Fig. 2, the integration of distributed generation sources, such as solar panels and energy storage systems, with local low voltage electrical networks in a complex system is depicted. By installing these systems

in proximity to electricity consumers, it is possible to positively alter the technical and economic indicators. By constructing the model in a system format, the condition of each electrical network is analyzed. The complex system created is analyzed for each scenario and compared with the real state of the electrical grid⁷ [1, 5, 24]. There are several advantages and opportunities in using this software for power supply systems. Table 2 below presents a comparison of the advantages and disadvantages of PSCAD and MATLAB [13].

From the comparison of advantages and disadvantages in the table, it can be seen that using PSCAD for the power supply system is considered efficient [13, 17].

In the process of designing the city power supply system, the problems associated with selecting optimal values for the nominal parameters of electrical grids can be addressed by ensuring the optimal condition of the technical and economic indicators of the power supply system⁸ [14].

In practice, to achieve energy efficiency in city power supply, it is necessary to calculate energy efficiency indicators through the application of distributed generation sources and use methods for optimizing the nominal parameters of the electrical grids. The following indicators have been established to achieve energy efficiency:

- reduction of the relative cost of electrical energy;
- reduction of electrical energy loss;
- minimization of environmental impact.

The technical-economic indicators of each electrical grids involved must be calculated individually. Each electrical grids that participates in the system has its own technical-economic indicators⁷ [2–4, 9, 11].

In the integrated distributed generation based, power supply system under consideration, the technical and economic indicators of each electrical network are analyzed. In this process, the parameters influencing the technical and economic performance of each part of the electrical network are identified⁸ [18].

Below, we present the expressions for calculating the technical-economic indicators of each network.

In this case, the given line costs (1) for a specified cross sectional area F , normalized to 1 km of its length, as a function of the calculated current I , can be written as follows:

$$C_L = K_L \cdot (p_L + E_N) + 3 \cdot I^2 \cdot R \cdot \tau \cdot C_W \cdot 10^{-3}, \quad (1)$$

where C_L – the normalized line costs, UZS MM (millions of UZS); K_L – the cost of building the line, UZS MM/km; p_L – deductions for depreciation, repair and maintenance of the line; E_N – regulatory efficiency factor; R – line resistance, Ohm/km; C_W – costs of covering electrical energy losses, UZS MM/kW·h; τ – maximum loss usage time, h.

The considered normalized costs (2, in million soums) as a function of the maximum load of the transformers:

Table 2. Comparison of the capabilities of the proposed simulation software package

Таблица 2. Сравнение возможностей предлагаемого программного пакета для моделирования

Criteria	PSCAD	MATLAB (Simulink)
Primary purpose	Simulation and analysis of power systems	Modeling and simulation of various systems
Interface	Intuitive and simplified	Complex with extensive functionalities
Specialization	Strong in electrical networks and power electronics	Versatile: electronics, mechanics, AI, etc.
Accuracy	High precision for time-dependent simulations	Wide-range precise modeling capabilities
Flexibility	Limited to power systems	Highly adaptable for various domains
Coding support	Primarily graphical interface	Allows MATLAB scripting and automation
Learning curve	Easier to grasp	Requires advanced learning
Integration	Limited compatibility with other software	Easily integrates with MATLAB toolboxes
Cost	Relatively affordable	Expensive, especially the full version
Application in power electronics	Less advanced, mainly voltage and current analysis	Strong support for power electronics
Parallel computing	Limited capabilities	Supports multi-core and cloud simulations
Real-time simulation	Can be used with PSCAD for real-time applications	Dedicated toolboxes for real-time systems

$$C_{TR} = K_{tr} \cdot (p_{tr} + E_N) + \Delta P_{no-l} \cdot T_{sw} \cdot C_{W.no-l} + \left(\frac{S_{max}}{S_{nom}}\right)^2 \cdot \Delta P_{sh.c.} \cdot \tau \cdot C_{W.sh.c.}, \quad (2)$$

where K_{tr} – the cost of the transformer (capital investment), UZS MM; ΔP_{no-l} , $\Delta P_{sh.c.}$ – the power losses of no-load and short-circuit modes of the transformer under nominal operating conditions, respectively, kW; T_{sw} , τ – annual operating time and losses, h; $C_{W.no-l}$, $C_{W.sh.c.}$ – the cost of electrical energy losses in no-load and short-circuit modes over the durations T_{sw} and τ , respectively, UZS MM/kWh; p_{tr} – the total percentage of deductions from the transformer's cost.

The total constituent costs of a solar photovoltaic power station consist (3) of the following:

$$C_{PV} = C_{Module} + C_{Inverter} + C_{Installation} + C_{Maintenance}. \quad (3)$$

The total constituent costs of electrical energy storage systems consist (4) of the following:

$$C_{ESS} = C_{Battery} + C_{Other additional costs} + C_{Installation} + C_{Maintenance}. \quad (4)$$

The technical-economic indicators of each component forming the city power supply system are calculated through the mathematical expressions presented above. For each case, the internal structure of the parameters to be determined must be explained in more detail. In this case, cable lines are used for medium, low voltage electrical grids as the power transmission lines [17, 22]. The calculations take into account the allowable limitations in relation to the cross sectional, area of the cable line. In the transformer substation, the optimal value of the rated full capacity of the power transformer is determined, considering the limitations. In the solar photovoltaic station, each component should be divided into individual nodes. The same approach is applied in energy storage systems [4–8].

Based on this, the total costs of the areas (5) taken as an object for the city power supply system are determined as follows:

$$C_{TOTAL} = C_{MV.L} + C_{TR} + C_{LV.L} + C_{PV} + C_{ESS}. \quad (5)$$

It is evident from the general expression that the technical-economic indicators, taken as the nominal value of each power grid component, are crucial for the system. The total value of all expenses incurred for the system is related to the parameters of the electrical grids that need to be optimized^{6,7} [2, 4, 17]. The parameters to be optimized in this case include the following [24]:

- cross sectional area of the medium voltage power network;
- length of the medium voltage power grid;
- rated capacity of the transformer substation;
- cross sectional area of the low voltage power grid;
- length of the low voltage power grid;
- rated capacity of the solar photovoltaic station;
- storage capacity of the energy storage system.

The Sequential Quadratic Programming method was selected to minimize the given objective function. This method is highly accurate and exhibits fast convergence when solving constrained optimization problems, and is distinguished by the following advantages:

- it performs effectively when the objective function and constraints are smooth and differentiable;
- the presence of well-defined boundaries for technical parameters justifies its application;
- at each iteration, a quadratic approximation enables rapid convergence toward the optimal solution.

The developed mathematical expressions represent the technical and economic indicators of the constituent elements of the object under consideration, and the data obtained through these expressions are presented in Table 3.

The optimal values of the parameters listed above provide the possibility to minimize the value of the costs incurred by the system. The problem of minimizing the total costs is accepted as the objective function, and the parameters are calculated based on this. The technical constraints to be included in the optimization process are of significant importance.

Table 3. Resulting values of technical and economic indicator calculation**Таблица 3.** Значения, полученные в результате расчетов технико-экономических показателей

No.	Network Component	Parameters	Calculation Expression	Value (Example)	Unit
1	Electric Transmission Line (Cable)	$F, I, R, T, C_W, K_L, p_L, E_N$	(1)	14.5	millions of UZS/km
2	Transformer Substation	$\Delta P_{no-L}, \Delta P_{sh.c.}, T_{SW}, T, C_{W.no-L}, C_{W.sh.c.}, K_{TS}$	(2)	36.4	millions of UZS.sum
3	Solar PV Power Station	Capacity, inverter, panels, installation costs	(3)	63.5	millions of UZS.sum
4	Energy Storage System	Storage capacity, system components	(4)	42.8	millions of UZS.sum
5	Total Costs	Sum of all component costs	(5)	152.4	millions of UZS.sum

The value of the constraints for each parameter must lie within the allowable range [3, 12, 23]. The developed comprehensive mathematical model is used for optimization purposes. It is advisable to apply modern methods for determining optimal parameters.

RESEARCH RESULTS AND DISCUSSION

Looking at the analysis of the necessary indicators for the use of distributed generation in the city power supply system, it is crucial to enhance the technical and economic indicators for each electrical network. In the complex scenario, for the area analyzed as the object, the integration of distributed generation, such as solar photovoltaic stations and energy storage systems, into low voltage electrical networks is achieved [17, 20]. The simulation model created in the PSCAD 4.6 software package is depicted in Fig. 3. In this study, the external network is considered at a medium voltage of 10 kV, while the low voltage side operates at 0.4 kV. A photovoltaic solar power station and an energy storage system are connected to the common low voltage busbar. For the system's electrical load, two public buildings have been selected. The schematic diagram presented in Fig. 3 covers a portion of the overall city area object shown in Fig. 1. In this case, only one of the four TS and its corresponding load from Fig. 1 – namely, TS2 (No. 420) – is considered.

The selection of TS2 (No. 420) was based on its typical load characteristics and central location within the studied area. By focusing on a single transformer substation, the simulation allows for a more detailed and accurate assessment of distributed generation impacts. Furthermore, the integration of distributed sources at the low voltage level enables the

evaluation of load balancing effects and energy loss reduction in a real world, city context. The simulation results also provide insights into voltage stability and peak load mitigation. This setup forms the foundation for further comparative analysis with traditional centralized power supply systems.

In the model, the structure of each electrical grid starting from the TS No. 420 transformer substation and the integration of the distributed generation are considered. The medium voltage grid is represented by a 10 kV cable line. The low voltage electrical grid includes cable lines leading to buildings 1 and 2, along with the distributed generation consisting of a photovoltaic solar station and an energy storage system. An inverter, which converts direct current to alternating current, is used for both systems. Technically, these could be installed separately depending on economic efficiency [14, 17].

In the proposed system, the transformer substation a nominal capacity of 100 kVA. To meet the electrical load, a hybrid setup has been implemented, featuring a 50 kW Jinko solar (Tiger Neo N-type JKM590N-72HL4-V) panel and an energy storage system (SUN-50K-SG01HP3-EU-BM4, Deye ARK 9-3,2 kWh HV), installed based on the spatial conditions of the buildings^{4,5,7}.

The SUN-50K-SG01HP3-EU-BM4 model presented below is a three-phase, high-capacity hybrid inverter designed for converting solar energy into electrical energy and for integration with energy storage systems. This device is primarily intended for use in large facilities, commercial centers, and industrial applications. Its technical specifications are comprehensively provided in Table 4.

The Tiger Neo N-type JKM590N-72HL4-V model presented below is a high efficiency,

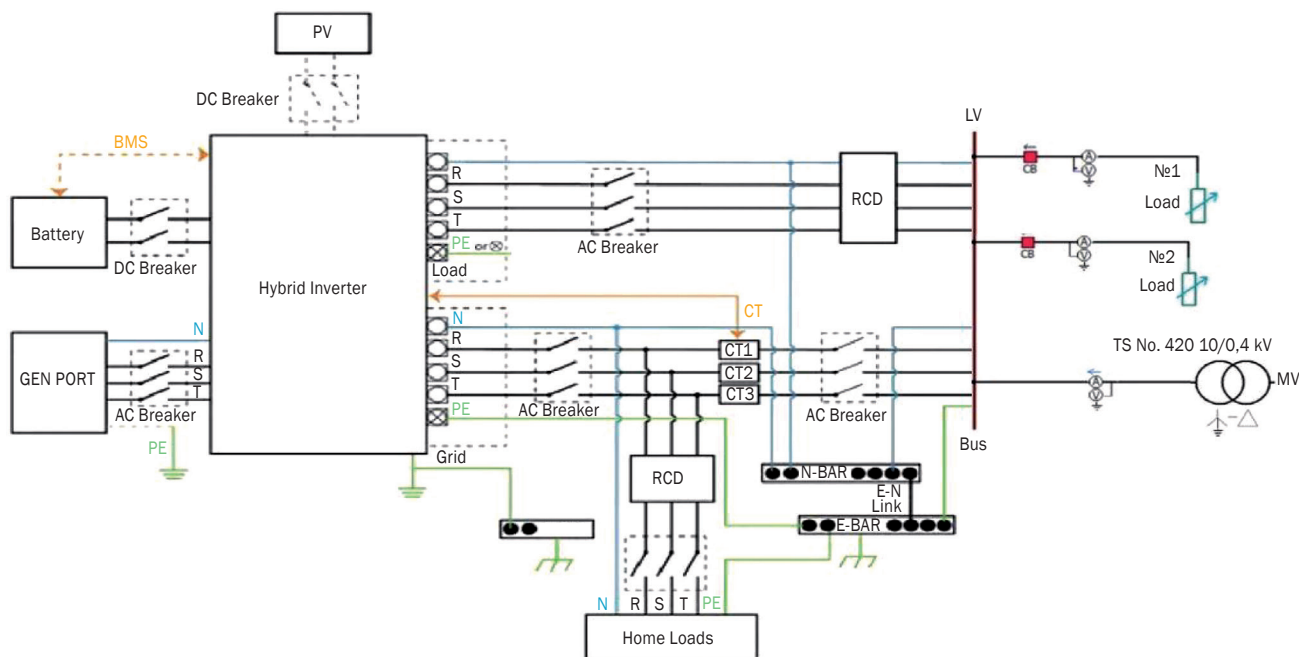


Fig. 3. The simulation model of the distributed generation connected to the transformer substation No. 420 in the research object

Рис. 3. Имитационная модель распределенной генерации, подключенной к трансформаторной подстанции № 420 в исследуемом объекте

high capacity monofacial solar panel designed for large-scale PV power plants. This solar module demonstrates both high output power and performance efficiency, maintaining stable operation even under high-temperature conditions. Due to its low power loss coefficients, it ensures effective energy generation. Its technical specifications are provided in Table 5. This panel is considered an ideal solution for

large industrial facilities and solar power stations.

Fig. 4 presents the annual electrical energy generation and load profile. From this graph, the average production capacity for annual consumption can be determined [15, 21]. The purpose of presenting this graph is to highlight that achieving a completely stable operating condition for the system is not feasible.

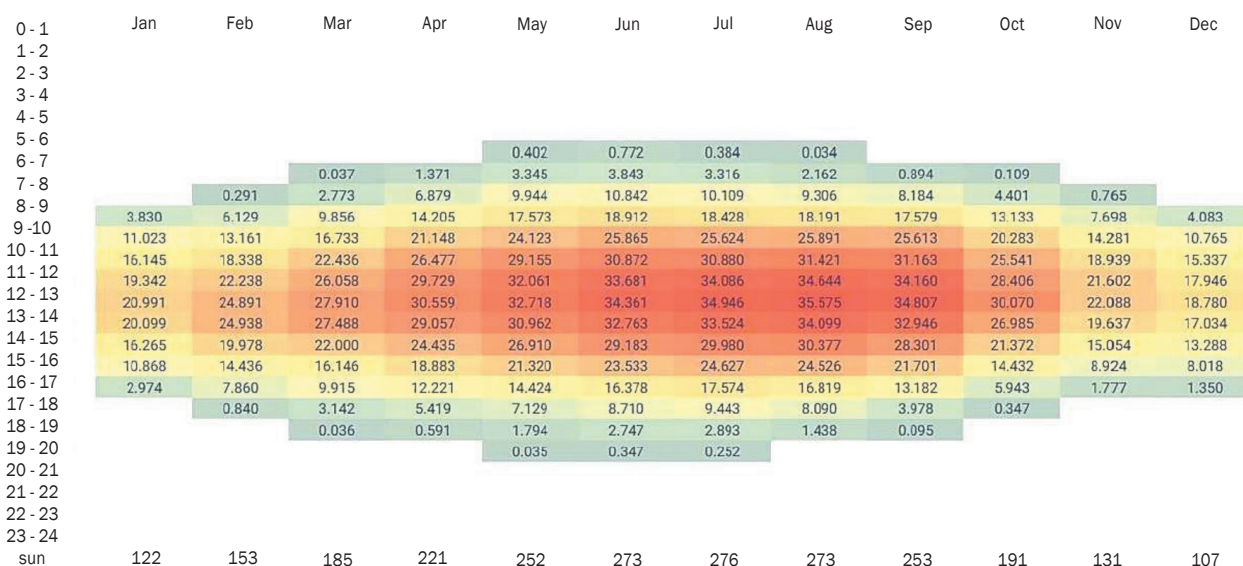


Fig. 4. Annual variation of electrical energy generation for a 50 kW, distributed generation system (JKM590N-72HL4-V)

Рис. 4. Годовые колебания выработки электроэнергии для распределенной системы генерации мощностью 50 кВт (JKM590N-72HL4-V)

Table 4. Technical characteristics of a three-phase hybrid inverter used for converting solar energy into electrical energy and integrating it with storage systems

Таблица 4. Технические характеристики трехфазного гибридного инвертора, используемого для преобразования солнечной энергии в электрическую и ее интеграции с системами накопления энергии

Model	SUN-50K-SG01HP3-EU-BM4
Battery Input Data	
Battery Type	Li-Ion
Battery Voltage Range (V)	160-800
Max. Charging Current (A)	50
Max. Discharging Current (A)	50
Number of battery input	2
Charging Strategy for Li-Ion Battery	Self-adaption to BMS
PV String Input Data	
Max. DC Input Power (W)	6500
Max. DC Input Voltage (V)	100
Start-up Voltage (V)	180
MPPT Range (V)	150-850
Full Load DC Voltage Range (V)	450-850
Rated DC Input Voltage (V)	600
PV Input Current (A)	36+36+36+36
Max. PV I_{sc} (A)	55+55+55+55
No. of MPP Trackers	4
No. of Strings per MPP Tracker	2
AC Output Data	
Rated AC Output and UPS Power (W)	50000
Max. AC Output Power (W)	55000
AC Output Rated Current (A)	75.8/72.5
Max. AC Current (A)	83.3
Max. Continuous AC Passthrough (A)	150
Generator input/Smart load / AC couple current (A)	75.8 / 150 / 75.8
Power Factor	0.8
Output Frequency and Voltage	50/60 Hz; 3L/N/PE 220/380; 230/400 Vac
Grid Type	Tree Phase
DC injection current (mA)	<0.5% I_n
Efficiency	
Max. Efficiency	97.60%
General Data	
Weight (kg)	75
Size (mm)	527Wx894Hx294D

Table 5. Technical specifications of high-efficiency monofacial solar panels used in large-scale photovoltaic

Таблица 5. Технические характеристики высокоэффективных односторонних солнечных панелей, применяемых в крупномасштабных солнечных электростанциях

Module Type	Tiger Neo N-type JKM590N-72HL4-V	
	Standard test conditions (STC)	Nominal operating cell temperature (NOCT)
Maximum Power (P_{max})	590 Wp	445 Wp
Maximum Power Voltage (V_{mp})	43.71 V	41.05 V
Maximum Power Current (I_{mp})	13.50 A	10.83 A
Open-circuit Voltage (V_{oc})	52.63 V	49.99 V
Short-circuit Current (I_{sc})	14.13 A	11.41 A
Module Efficiency STC (%)	22.84%	
Operating Temperature	-40~+85	
Maximum system voltage	1000/1500 VDC (IEC)	
Power tolerance	0~+3%	
Temperature coefficients of P_{max}	-0.29%	
Temperature coefficients of V_{oc}	-0.25%	
Temperature coefficients of I_{sc}	0.045%	
NOCT	45±2	

To address this limitation, the development of systematic control devices will be necessary in the future.

The load condition applied to the local electrical network is regulated. In cases of low load, the energy storage system operates in charging mode, while in overload situations, it functions in discharging mode. The performance of the model in simulation mode is analyzed, and the results are presented in Table 1 for the state analysis after integrating the distributed generation. The analysis for a single TS No. 420 transformer substation is shown in Table 6.

In this study, several parameters affecting the normal operating condition of the system have been considered, including energy losses, peak overload periods, voltage drops in electrical networks, and the annual number of system losses. Reducing the values of these parameters contributes to improving the technical and economic performance of the system and enhancing the reliability of the power supply [16, 17].

A comparative analysis has been conducted by utilizing existing methods for these electrical networks. Based on this analysis, Table 7 has been developed to compare the specific values of the parameters presented in Table 6 [2, 9, 18, 21].

From Table 7, it can be observed that applying the proposed approach using a PSCAD-based model for low voltage electrical networks can enhance energy efficiency and power supply reliability [2, 7, 23].

As a logical continuation of this approach, the implementation of control systems and the optimization of energy efficiency parameters will contribute to minimizing the overall environmental impact in a comprehensive manner [9, 16, 18].

The electrical load graph of the existing state and the analysis of the electrical load graph after adjusting the model to the load condition have been carried out. The change characteristics of the electrical load graph for the given condition are illustrated in Fig. 5. During the 24 hour period, the electric load profile reaches a steady state condition. This is achieved through the optimal control of distributed generation sources [3, 6, 11].

From this chart, it can be observed that by integrating a photovoltaic solar power station and an energy storage system into the low voltage electrical networks, the energy storage systems charge during periods of low load, while the local electrical networks are supplied with power through distributed

Table 6. Values of parametric indicators in the electrical network obtained after constructing a model of the distributed generation electrical supply system for the transformer substation No. 420

Таблица 6. Значения параметрических показателей в электрической сети, полученные после построения модели системы электроснабжения с распределенной генерацией для трансформаторной подстанции № 420

Electrical grid address (TS and cable line complex)	Building number	The annual share of losses in the transformer substations and outgoing lines, %	Annual overload in the electrical grids, hours	Voltage loss in the electrical grids, %	The annual number of interruptions occurring in the power supply system
TS No. 420	No. 1 and 2	5	2700	2.9	8

Table 7. Comparative values of parametric indicators in the electrical grid after constructing the distributed generation-based power supply system model for transformer substations No. 420

Таблица 7. Сравнительные значения параметрических показателей в электрической сети после построения модели системы электроснабжения на основе распределенной генерации для трансформаторной подстанции № 420

Comparison of the developed scientific approach	The annual share of losses in the transformer substations and outgoing lines, %	Annual overload in the electrical grids, hours	Voltage loss in the electrical grids, %	The annual number of interruptions occurring in the power supply system
Values obtained before model implementation	8	3400	4	12
Results obtained from the developed model	5	2700	2.9	8
Results obtained in the control system using classical optimization and the model built in Simulink	6.3	3300	3.6	11

generation during peak load periods. As a result, the electrical load graph becomes more balanced. Due to the growing demand for “Green energy” in the Republic of Uzbekistan, the use of distributed generation is justified. Research findings indicate that in some electrical networks, the values of energy losses and voltage drops exceed the permitted values. The use of distributed generation in city areas, with automatic adjustment based on load fluctuations, can reduce energy losses by up to 2.9%. By leveling the electrical load graphs, it is possible to extend the reliable operation period of high voltage electrical networks [11, 18].

There are technical limitations in the conducted research. In this study, the nominal voltage is considered as a system with $U_i < 1000$ V ($I_i < I_{ac}$). The model primarily focuses on technical and economic indicators, while long term operation and discounted costs are not taken into account. The system, in its comprehensive state, forms a multi approach function. For medium voltage, it is advisable to consider $10 < U_i < 35$ kV ($I_i < I_{ac}$), as introducing high voltage networks exceeding 35 kV into small city areas may lead to construction constraints [19, 22].

CONCLUSION

Based on the research conducted to scientifically justify the use of distributed generation in the city small district power supply system, the following conclusions can be drawn for this article:

1. The indicators for the use of distributed generation were analyzed to ensure the continuous supply of high-quality and reliable electricity to consumers in the small district of the city.
2. The operational modes of the electrical networks and the mathematical models of their technical-economic indicators in the

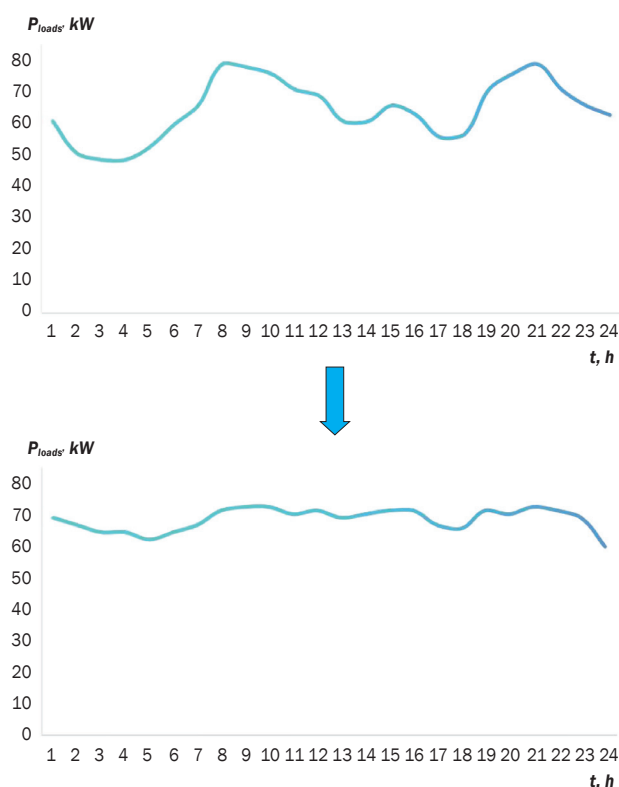


Fig. 5. Expected load variation chart for the daily electrical load in the case assigned to transformer substation No. 420

Рис. 5. График ожидаемых изменений нагрузки для суточной электрической нагрузки трансформаторной подстанции № 420

small district power supply system were analyzed.

3. An imitation model was developed for the use of distributed generation in the electrical networks of the existing object in the city area, and the adjustment of the electrical load graph to a steady state was considered.

4. As a result of using distributed generation in the electrical networks of the existing object in the city area, the potential to increase the efficiency of the parametric indicators and reduce electricity losses in these networks by up to 2.9% was created.

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