V International Scientific and Technical Conference Actual Issues of Power Supply Systems

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Mirkomil Melikuziev [1, a)], Oxun Tashanov [1], Fazliddin Usmonov [1], Mukhriddin Tuyqulov [2]

[1]Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan
[2]Navoi State University of Mining and Technologies, Navoiy, Uzbekistan

Corresponding author: melikuzievmirkomil@gmail.com

Abstract. This paper develops a method for selecting the parameters of urban distribution electrical networks, taking into account the integration of distributed generation (DG) sources into the network. The study primarily focuses on low-voltage distribution networks, where high electrical load density in certain network segments can lead to voltage drops, energy losses, and reduced operational efficiency. To address these issues, the use of photovoltaic (PV) systems and battery energy storage systems (BESS) as distributed generation sources is proposed. The presented method aims to optimize the parameters of urban distribution networks, including cable cross-sectional area, line length, and the capacity of supply transformers, while considering the location, capacity, and operational modes of DG sources. The optimization process is carried out based on the particle swarm optimization (PSO) algorithm and load flow calculation methods. This approach enables the evaluation of network performance under various operational conditions..

INTRODUCTION

At present, due to the increasing demand for electricity across the country, the expansion of urban areas, population growth, and the diversification of electricity generation sources, the scientific justification for the reconstruction and modernization of existing distribution networks, as well as the optimal selection of their operational modes and parameters, has become a pressing issue. In the territory of the Republic of Uzbekistan, the majority of electricity consumed by end-users is generated by thermal power plants, currently accounting for over 80% of total electricity production. In addition, the share of hydropower plants and renewable energy sources is steadily increasing [1, 3].

Given the country's high solar potential, the use of solar energy for electricity generation is developing rapidly. Uzbekistan is distinguished by abundant solar energy resources, long hours of sunshine, and extended daylight duration. The average global horizontal irradiance (GHI) on a horizontal surface is approximately 4.52 kWh/m²/day, varying between 4.0 and 5.0 kWh/m²/day across the country. The average direct normal irradiance (DNI) is approximately 4.44 kWh/m²/day, ranging from 3.03 to 5.27 kWh/m²/day nationwide [1-2].

By 2030, the country aims to increase the installed capacity of solar and wind energy from 8 GW to 12 GW, of which 7 GW is expected from solar energy and 5 GW from wind energy. Considering that these generation sources will be installed close to electricity consumers, significant voltage rise and other operational challenges are likely to occur in urban distribution networks. The integration of photovoltaic (PV) plants and energy storage systems into local networks introduces a number of issues that must be addressed. Consequently, the optimal selection of parameters for existing or planned urban distribution networks is of critical importance [1, 3, 7, 14, 20].

EXPERIMENTAL RESEARCH

The object of this study is a small residential microdistrict located in the Chilanzar district of Tashkent city, Republic of Uzbekistan. The research focuses on determining the optimal parameters of distribution networks for local electricity systems as a result of integrating distributed generation (DG) sources. The study also aims to provide initial data for design institutes for similar types of projects in the region, serving as a scientific guideline for planning newly constructed urban distribution networks [4-5, 15, 19].

In this research, a novel method for selecting parameters of low-voltage urban distribution networks is developed. The main objective is to address issues that arise in network sections with high electrical load density, such as voltage drops, energy losses, and reduced operational efficiency [6, 17, 20].

Within the framework of the experimental analysis, the integration of photovoltaic (PV) systems and battery energy storage systems (BESS) as DG sources is considered. These sources are expected to positively influence network operation, particularly by maintaining voltage stability during peak loads and reducing losses.

As an experimental model, a test case is developed based on the urban distribution network structures shown in Figure 1 for the purpose of this study [6, 10, 18].
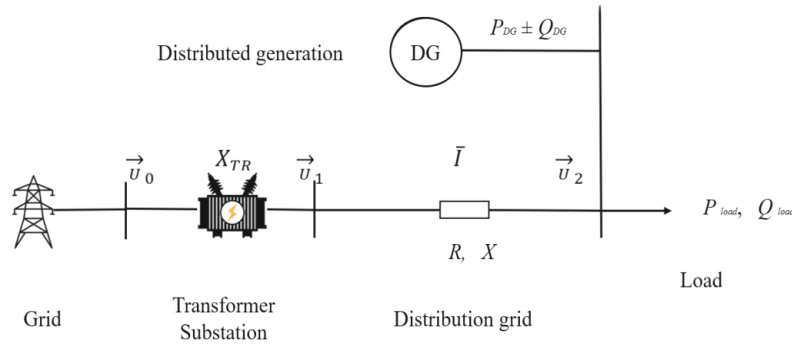

FIGURE 1. Single-line diagram of the updated urban power supply system.

It can be observed that the elements of the electrical networks between the transformer substation and the consumers are considered. In each experimental study, the following parameters are treated as optimization objectives [2, 4, 11]:
- cable cross-sectional area;
- line length;
- capacity of the supplying transformer.

The optimization process was carried out using the particle swarm optimization (PSO) algorithm. For each combination, the network performance was evaluated using the load flow calculation method, considering the following indicators [1-5, 20]:
- voltage drop level;
- active power losses;
- overall operational efficiency.

Initially, the parameters to be optimized were developed in relation to the total system costs. Due to the presence of multiple constraints in the system, the initial optimization was performed for individual network sections using the least squares method. Subsequently, the complex case was addressed using the particle swarm optimization algorithm [6, 8, 17].

First, the overall load balance of the electrical network is established. For this, photovoltaic (PV) systems and battery energy storage systems (BESS) were considered as distributed generation (DG) sources in their optimal configuration [11, 19]. In this context, the equivalent electrical load based on the total load flow, i.e., the power flowing from the network, is determined using the following expression (Equation 1):

$$P_{ekv} = P_{load} - (P_{PV} \pm P_{BESS}), \tag{1}$$

here: $P_{load.}$ - total electrical load of the distribution network [kW]; P_{PV} - total power injected into the system from the photovoltaic (PV) plant [kW]; $P_{BESS.}$ - total power supplied to the system from the battery energy storage system (BESS), with optimal power determined based on charging (-) and discharging (+) [kW].

To determine the optimal parameters of the distribution network, it is necessary to calculate the system's objective function and its constituent elements. The objective function is defined as the total equivalent cost of the system. The system under consideration consists of a distribution network up to 1000 V, its source transformer substation, and distributed generation (DG) units. For each component, a mathematical model of the associated costs is developed. Based on these expressions, the optimization problem is solved with respect to the system parameters through the objective function [7, 15-18].

The annual equivalent costs of a distribution network up to 1000 V include the sum of capital expenditures and the cost of electricity losses, and are calculated using the following expressions (Equation 2):

$$C_{LV} = p_{\Sigma L} \cdot (K_{LV0} + K_{LVF} \cdot F_{LV}) \cdot l_{LV} + \Delta P_{LV} \cdot \tau \cdot c \cdot 10^{-5}, \tag{2}$$

$$p_{\Sigma L} = p_N + p_{amt}, \tag{2a}$$

here: $p_{\Sigma L}$ – overall discount coefficient for capital expenditures; p_N – normative coefficient for effective utilization of capital expenditures [0.12]; p_{amx} – depreciation discount coefficient for maintenance and repair, 5% of capital expenditures for cable lines up to 10 kV; τ – maximum loss time, hours/year; c – cost of lost electrical energy [kW·h], in [UZS/kWh].

One of the most significant factors affecting the total cost is the length of the distribution network line up to 1000 V. The length of the network line up to 1000 V depends on a number of factors, including load density, transformer capacity, network configuration, construction characteristics, and other relevant parameters [12, 16, 19].

Empirical expressions provided in the literature for determining the lengths of low-voltage (*up to 1000 V*) lines within a single transformer substation (TS) area have a number of limitations and can yield different results when applied to the same initial data.

Therefore, based on a generalized analysis of network construction, it is necessary to determine the total comparative lengths of distribution networks with voltages up to 1000 V. These relationships are also required to mathematically describe the total cost function of the distribution network. If the electrical load is uniformly distributed across the considered area, the total length of (*cable*) lines in that area depends on: the area of the region, F; The density of power consumption points, represented by the distance d between adjacent connection points; The network construction and configuration scheme [13, 15, 18].

When the load is evenly distributed throughout the area, it is economically reasonable to place the supply source at the center of the considered region. If the network is constructed according to a radial scheme, this scheme may exhibit different structural characteristics and total network lengths even when consumer locations and numbers are the same. This also applies to a network with a double-main scheme.

Consequently, an expression for the length of the low-voltage (*up to 1000 V*) line associated with a single transformer substation is developed, with its final form represented by [9] the following expression (Equation 3):

$$l_{LV} = \frac{\lambda_{LV} \cdot S_{TS}^{3/4} \cdot M_{LV}^{1/2}}{\sigma^{3/4}}, \tag{3}$$

here: λ - coefficient dependent on the configuration of the low-voltage distribution network; M - number of lines that can originate from the transformer substation (TS); S_{TS} - rated capacity of the transformer substation [kVA]; σ - electrical load density, determined as the ratio of the total load to the area of the region it serves, calculated according to Equation 4 [kW/km²], i.e.,:

$$\sigma = \frac{P_{ekv}}{F_{area}}, \tag{4}$$

For a transformer substation (10/0.4 kV) connected to the main power supply, which provides consumers with a sufficiently stable power supply [10, 14], the total costs - both dependent and independent of the capacity of the transformer within the substation - are expressed in the following form (Equation 5):

$$C_{TS0} = p_{\Sigma TS} \cdot K_{TS0} + C_0, \tag{5}$$

$$p_{\Sigma TS} = p_N + p_{amt}, \tag{5a}$$

$$C_{TS} = C_S \cdot S_{TS} + C_{TS0}, \tag{5b}$$

here: $p_{\Sigma TS}$ – overall discount coefficient for capital expenditures for transformer substation construction; p_N – normative coefficient; p_{amx} – depreciation allocations for maintenance and repair of substation equipment, which can be assumed to be 10.3% of the capital expenditures [8, 16, 19].

If the total equivalent costs of the distribution network are expressed mathematically based on the contributions from the transformer substation, low-voltage lines, and distributed generation (DG) sources, this can be represented in the following form (Equation 6):

$$C_{total} = C_{TS} + C_{LV} + C_{TG}, \quad [thousand\ soms] \tag{6}$$

here: $C_{TG} = C_{\Sigma\ PV} + C_{\Sigma\ BESS}$, [thousand soms] (6a)

To determine the optimal parameter values, it is first necessary to take technical constraints into account. In this process, the main constraints for the electrical networks and distributed generation (DG) sources are identified. These constraints are considered for the balance of consumed, generated, and lost power [4, 7, 9, 18].

The electrical load density is determined in accordance with the condition specified in Equation 7:

$$\sigma_{n,t} \le \sigma_n^{max}, \tag{7}$$

For the low-voltage distribution network, the main requirement is to verify the line for overheating and ensure that the voltage drop does not exceed the permissible value of 5%. This is calculated according to Equation 8:

$$I_{i.t} = \frac{P_{ekv}}{\sqrt{3} \cdot U_n} \le I_{max}(A_i^{disc}), \tag{8}$$

$$\Delta U_{real} = \sqrt{3} \cdot I_{i.t} \cdot (r_0 \cdot cos\varphi + x_0 \cdot sin\varphi) \le \Delta U_{norm}^{max}, \tag{8a}$$

Since we ensure the integration of distributed generation (DG) sources into the transformer substation and the low-voltage distribution network [6, 8, 13], it is necessary to consider their spatial constraints. The constraints for the PV and BESS systems are determined according to Equation 9 as follows:

$$0 \le P_{PV,n} \le \rho_{PV}F_n, \qquad 0 \le E_{BESS,n} \le \rho_{BESS,E}F_n, \qquad 0 \le P_{BESS,n} \le \rho_{BESS,P}F_n, \tag{9}$$

In accordance with the above conditions, the loading constraints of the transformer substation, based on its load status, are determined according to Equation 10 as follows:

$$\sum_{n \in N_i} (P_{load,n,t} - P_{PV,n,t} - P_{BESS,n,t}^{dis} + P_{BESS,n,t}^{char}) \le S_j^{disc}, \tag{10}$$

Experimental tests were carried out under various operational conditions. All the mathematical expressions and models presented above were derived using the least squares method. For each scenario, the performance of the network was evaluated based on the optimized parameters obtained using the proposed method and compared with conventional parameter selection approaches. The results indicate that the proposed approach improves the efficiency of the electrical network, reduces voltage drops, and significantly decreases energy losses [4, 8, 11, 16].

RESEARCH RESULTS

As a result of the conducted studies, the effectiveness of the proposed method for selecting the optimal parameters of urban distribution networks was tested in a practical case. The study object was the electrical supply system of a microdistrict in the Chilanzar district of Tashkent city. Due to the high electrical load density in this area, issues such as voltage drops and energy losses are observed [1, 5, 14, 19].

In this research, low-voltage distribution networks up to 1000 V were considered, integrating photovoltaic (PV) sources and battery energy storage systems (BESS). The cable cross-sectional area (F) and transformer capacity (S) were optimized. The main objective was to minimize the total system costs while simultaneously satisfying technical constraints related to voltage, electrical load density, and transformer loading [19-20].

The optimization process was carried out using the particle swarm optimization (PSO) algorithm in combination with load flow calculation methods [4, 14]. In the PSO algorithm, for each solution represented by the particle combinations of cable cross-sectional area (F) and transformer capacity (S), the load flow was calculated, and the following indicators were determined: voltage drop, electrical energy losses, and operational efficiency. In each iteration, the particles' personal best and global best solutions were updated, progressively converging toward the optimal solution [4, 8, 14].

Based on mathematical modeling, the objective function, taking constraints into account, is formulated in the resulting form as shown in Equation 11:

$$C_{total} = C_{TS}(S) + C_{LV}(F) + C_{PV} + C_{BESS}, \tag{11}$$

In solving the problem, the particle swarm optimization (PSO) algorithm and load flow calculations (LinDistFlow model) were applied. Each particle represented potential values of F and S, which were iteratively adjusted to comply with industrial standards. At each step [16], the load flow was calculated, voltages, currents, and transformer loadings were determined, and the objective function was evaluated. The PSO algorithm was implemented based on the equations presented in Equation 12:

$$\vartheta_k(t+1) = \omega \cdot \vartheta_k(t) + c_1 \cdot r_1(pbest_k - x_k(t)) + c_2 \cdot r_2(gbest - x_k(t)), \tag{12}$$

$$x_k(t+1) = x_k(t) + \vartheta_k(t+1), \tag{12a}$$

subsequently, the values were adjusted to discrete standard levels..

As a result, the optimal values were determined as shown in Equation 13:

$$F^* = argmin_{F \in A} \, C_{total}(F, S), \quad S^* = argmin_{S \in S} \, C_{total}(F, S), \tag{13}$$

Here, A and S represent the standard sets of cable cross-sectional areas and transformer capacities, respectively.

When selecting the capacity of the PV system, load density and demand play a key role [8, 17].

Low load density: The available area for the PV system is sufficient, as the panels require more space. The PV capacity can range from 50% to 80% of the system's maximum generation capacity (in some cases, a load-following PV operation is applied). Medium or high load density: The available space for panels may be limited → PV capacity needs to be optimized. It is recommended to adjust the PV capacity to match the load peaks [9, 16].

The energy capacity and power of the BESS depend on the load density and the PV generation profile: Energy capacity (kWh): Determines how long the BESS can cover the load. Power (kW): Determines the maximum power the BESS can supply at any given moment. Low load density: A larger battery capacity is required, as PV generation often cannot fully cover the demand. High load density: The battery is used to cover short peaks, so the required energy capacity can be relatively small [7, 11, 19].

The results calculated based on the obtained mathematical expressions are presented in Table 1 in numerical form. These values show the variations of cable cross-sectional area, transformer rated capacity, and line length for a wide range of load densities [1-3].

TABLE 1. Dependence of main distribution network parameters on load density

1	σ, MW/km^2	2	4	8	12	16
2	S_{TS}, κVA	303	607	922	1116	1358
3	F_{LV}, mm^2	92	106	121	139	142
4	l_{LV}, km	1,425	1,181	0,998	0,852	0,791

The obtained results indicate that the proposed approach enables a highly efficient process for selecting cable cross-sectional areas and transformer capacities. The optimization method based on the particle swarm optimization (*PSO*) algorithm allows for the reduction of electrical energy losses, maintaining voltage drops within permissible

limits, and decreasing capital expenditures. At the same time, all constraints of the electrical load flow are fully satisfied, and the system's technical parameters are maintained at the required level [6, 11, 14].

The proposed methodology demonstrates particularly high efficiency in modern distribution networks with integrated photovoltaic (*PV*) plants and energy storage systems (*BESS*). This approach ensures not only economic performance but also technical stability [3, 7, 15, 18].

The study results show that selecting excessively small cable cross-sections leads to voltage drops exceeding the allowable limits, while overly large cross-sections are economically inefficient. Therefore, the cross-sectional values chosen using the PSO algorithm are balanced from both technical and economic perspectives [8].

A similar trend was observed in selecting transformer capacities: undersized transformers result in excessive loading, whereas oversized transformers incur unnecessary capital costs. The optimal transformer capacities obtained through PSO ensure efficient operation and maintain the loading coefficient within the normative range.

The significant impact of load density on the main technical indicators of the electrical network was also noted. Parameters selected using the PSO algorithm allowed the network to maintain stability without exceeding the permissible voltage drop limits [8, 11-14].

Overall, compared to conventional calculation methods, the proposed optimization approach improves energy efficiency, enhances voltage stability, and reduces total costs. Additionally, the rapid convergence capability of the PSO algorithm and its ability to solve complex optimization problems with high accuracy were confirmed as major advantages of this method [2, 9, 17].

CONCLUSIONS

The conducted studies demonstrate that using the particle swarm optimization (*PSO*) algorithm in combination with load flow calculation methods provides high efficiency in selecting the optimal parameters of urban distribution networks. Based on experimental calculations carried out in the Chilanzar microdistrict, the following results were obtained: Optimal cable cross-sectional area (*F*): The most economically and technically feasible values were found within the range of 95-150 mm². Smaller cross-sections led to excessive voltage drops, while larger cross-sections resulted in unnecessary capital expenditures; Optimal transformer capacity (*S*): Transformers within the range of 400-1000 kVA proved effective for areas with high load density. In this case, the transformer loading coefficient remained within the normative 70-80% range, with no excessive loading observed. The proposed optimization method reduced electrical energy losses by 12-15% and improved voltage stability by 8-10%. The PSO algorithm ensured rapid convergence and high accuracy even in complex optimization problems. Compared to conventional methods, the PSO-based results demonstrated clear economic and technical advantages. Overall, the proposed approach, which accounts for the integration of distributed generation sources (*PV* and *BESS*), allows for a reduction in capital expenditures, maintains voltage drops within permissible limits, significantly decreases energy losses, and enhances the technical reliability and economic efficiency of the network. This methodology can serve as a scientific and practical foundation for designing new electrical networks and modernizing existing ones in urban areas.

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