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Determination of the Optimal Value of the Technical and Economic Parameters of Electrical Networks in City Power Supply

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Abstract: The relevance of the study lies in the fact that in the power supply system there is a problem of choosing the parameters of the elements of the electrical network according to technical and economic indicators. The increase in the number of electricity consumers is associated with the expansion of energy consumption facilities in urban and industrial enterprises, as well as in agriculture. One of the solutions to this problem is the choice of optimal parameters of power transmission lines that provide consumers with electricity, for example, the cross-section of the surfaces of the lines at the optimal value. It is important to correctly determine the location of the transformer substation that provides electricity to the territory in combination with the cross-sectional surface of the line. Study of the factors influencing the technical and economic parameters to be selected and their mathematical expressions. A small micro districts belonging to the area of urban electricity supply was chosen as the object of the study. To determine the optimal parameters, mathematical expressions have been developed using the method of mathematical expectations and matrices in determining capital and operating costs. The results of the study showed that issues related to the establishment of permissible values of electrical load and voltage when determining the cross-sectional surfaces of lines, as well as all factors affecting the determination of terrain coordinates, can change the technical and economic value of optimal parameters. The parameters obtained as a result of solving the problems discussed in this article are used in the distribution electrical networks of the power supply system (0,4/6/10 kV), as well as during the construction of transformer substations on the territory.

Keywords: reduced costs, optimal location, power losses, matrix, line sections.

Introduction. Currently, reducing electricity consumption and improving energy efficiency are priorities for the development of the electric power system in accordance with the Development Strategy of the Republic of Uzbekistan until 2030. In the power supply system, the indicators of electricity consumption of industrial enterprises, cities and consumers of agricultural electricity do not form a uniform electrical load. The electrical load of electricity consumers on the territory of the city per unit of time is considered uneven. Therefore, the choice of optimal parameters of the elements of the distribution network in the city is a complex process. At the same time, the issue of determining the optimal value of the parameters of power lines and transformer substations according to technical and economic indicators is relevant.

As a result of an increase in the number of consumers of electric energy and the expansion of territories, an increase in demand for electric energy produced, transmitted and quality indicators of which are in the acceptable range, it is necessary to determine the optimal values of the cross-sectional surface of power transmission lines providing territories, to determine the optimal values of the costs of their laying.

At the same time, the question of the total number of transformer substations of 6-10/0,4 *kV* located in the received zones, the optimal amount of power and determining their location must be solved using mathematical expectations, methods and techniques.

The purpose of our work is to study the determination of the technical and economic optimal parameters of elements of distribution electric networks that provide consumers of electric energy in various regions. At the same time, parameters affecting the technical and economic indicators of the power supply line with a voltage of up to 1000 *V* and transformer substations with a voltage of 6-10/0,4 *kV* were obtained.

The scientific significance of the study lies in the definition of mathematical expressions for determining the optimal parameters of the elements of the distribution electrical network using mathematical expectations and methods.

The practical significance of the study lies in the fact that, based on the possibilities of the theoretical data obtained, by introducing them into existing distribution electric networks, it is possible to reduce the amount of total costs for electric networks, to obtain their optimal values. The results of the work will be useful if they are implemented in small neighborhoods in the city.

The main part. The task of determining the optimal location of the transformer substation (*TS*) should be solved taking into account the criteria of technical and economic efficiency.

In this paper, the criterion of the minimum of the reduced costs, which in general can be represented as a dimensionless target function (*TF=Z*), acts as a criterion of technical and economic efficiency.

The choice of the optimal location of the TS depends on the length of the cable line *(CL)* network from the TS to the input and distribution device (*IDD*) of consumers and on the cost of renting the territory.

Routes for laying *CL* on the territory of the city should also be determined taking into account the criteria of technical and economic efficiency. Since different plots of land through which the communications of the *PS* lines pass have different costs. The costs associated with the laying of *CL* and their maintenance and repair also have different costs at different sites. When laying a cable on the territory of the carriageway, the cost of work increases sharply due to the need to open and restore the pavement, etc.

When solving the technical optimization problem of determining the optimal location of the *TS*, it is necessary to determine the optimal route for laying the *CL*.

As a tool for determining the optimal route and the length of the *CL*, it is proposed to use a modification of the wave front algorithm - the fast marching algorithm [1-2, 5].

Z contains three components:

1. Capital expenditures - *K*;
2. Operating costs - Q_t;
3. Expenses related to compensation of electricity losses - ΔW.

Let's consider these components in the context of the task of determining the optimal routes for laying *CL*.

The capital costs for the construction of the *CL* should take into account the costs of equipment (cables, cable fittings, couplings) and construction and installation work. We believe that the cost of the construction of a *CL* is proportional to its length [6], thus, for *K* we get:

$K = c_0^{cl} \cdot L,$ (1)

where c_0^{cl} - the unit cost of the construction of *CL*, thousand sum./m.

Value c_0^{cl} — it is differentiated depending on the rated voltage, the cross-section of the core material, the type of cable, the method of laying, the number of cables in the trench and the rental value of the land allocated for laying *CL*.

Operating costs for *CL* are primarily associated with emergency maintenance of damaged cable sections. The probability of damage to the overhead line due to the fault of the organization operating the power supply *(PS)* network is much less than the probability of damage to the overhead line. Based on the above arguments, this type of costs, in the context of the task of determining the optimal routes for *CL*, is not taken into account.

The costs associated with the compensation of electricity losses *ΔW* are found from the expression:

$$\Delta W = \Delta P_{\text{Max}} \cdot \tau, (2)$$

where ΔP_{Max} - power losses in the maximum load mode of the network, τ - the number of hours of maximum losses during the considered period of network operation.

The number of hours of maximum losses can be approximately determined by the empirical dependenceи [7, 15]:

$$\tau = (0{,}124 + \text{T}_{\text{Max}} \cdot 10^{-4})^2 \cdot 8760, (3)$$

where T_{Max} - the number of hours of maximum load usage per year.

According to [6, 13], T_{Max} = 5400 hours for an average city, therefore, $\tau \approx 3862$ hours per year.

Assuming that the load schedules remain unchanged during the period under consideration on the order of *T*=30 years. For a concentrated load at the end of the line *P*, using the ratio (1) and moving from voltage loss to power loss for *ΔW*, we obtain:

$$\Delta W = \sqrt{3} \cdot \frac{P^2}{U_n^2} \cdot L \cdot \tau \cdot (r_0 \cdot cos\varphi + r_x \cdot sin\varphi), (4)$$

For the purposes of this study, it is more convenient to switch to unit values measured in thousand sum./m. and units of energy in kW·h.

Substituting the value of τ and $L=10^{-3}$ *km* and taking into account that $r_x \approx 0{,}06$ *Ohm/km*, $cos\varphi \approx 0{,}98$ (for household consumers), we neglect the inductive component of the cable resistance for specific electricity losses during the year, we get the expression (in *kW·h/m*)

$$\Delta\omega = 6{,}55 \cdot 10^{-3} \cdot \frac{P_{\text{Max}}^2}{U_n^2} \cdot r_0, (5)$$

Substituting (4) and (5) into (1), we obtain an expression for the *Z* of the relative reduced unit costs per one meter of *CL* during the entire service life

$$z_0^{cl} = \frac{c_0^{cl} + 6{,}55 \cdot 10^{-3} \cdot c_{ls} \cdot r_0 \cdot \sum_{t=1}^{T} (\frac{P_{\text{Max}}}{U_n})^2 \cdot (\frac{1+k_{wc}}{1+k_{dr}})^{t-1}}{c \cdot \sum_{t=1}^{T} W_{an}^{cl} \cdot (\frac{1+k_{wc}}{1+k_{dr}})^{t-1}}, (6)$$

The denominator (6) contains the total cost of the electricity transmitted over the cable during the entire service life, which ensures dimensionless z_0^{cl} and independence from the economic conjuncture.

Imagine $W_{an}^{cl} = P \cdot \tau_{\text{Max}}$, where τ_{Max} = 5400 h. [6, 11], then for z_0^{cl} we get:

$$z_0^{cl} = \frac{c_0^{cl} + 6{,}55 \cdot 10^{-3} \cdot c_{ls} \cdot r_0 \cdot \sum_{t=1}^{T} (\frac{P_{\text{Max}}}{U_n})^2 \cdot (\frac{1+k_{wc}}{1+k_{dr}})^{t-1}}{c \cdot \sum_{t=1}^{T} P \cdot \tau_{\text{Max}} \cdot (\frac{1+k_{wc}}{1+k_{dr}})^{t-1}}, (7)$$

The cost of electricity losses is c_{ls}, determined from (c_{ls}).

From the values of z_0^{cl} for each square meter, a matrix of unit costs Z_0^{cl} (9) is formed, the columns of which are local *X* coordinates, and the rows are *Y* coordinates. The sampling step is 1 m.:

$$Z_0^{cl} = \begin{bmatrix} z_0^{cl}(1,1) & z_0^{cl}(1,2) & \cdots & z_0^{cl}(1,n) \\ z_0^{cl}(2,1) & z_0^{cl}(2,2) & \cdots & z_0^{cl}(2,n) \\ \vdots & & \ddots & \vdots \\ z_0^{cl}(k,1) & z_0^{cl}(k,2) & \cdots & z_0^{cl}(k,n) \end{bmatrix}, (8)$$

Figure 1 shows the matrix Z_0^{cl}, for a segment of the weighted Vorono diagram, in shades of gray, which is determined similarly with the ratio (2), each shade corresponds to the definition of the value z_0^{cl} (7), 1 pixel corresponds to 1 m^2.

The matrix Z_0^{cl} serves as a weight matrix for the algorithm for determining the elements of the matrix of geodesic distances $D_{i,G}^{cl}$ and optimal routes of *CL*. In this study, "Fast marching" was used [3-5], it is possible to use other algorithms for finding optimal paths on graphs, e.g. the "A-star" algorithm or Deykstry algorithm.

The elements of the matrix of geodetic distances $D_{i,G}^{cl}$ are the costs of laying a cable from a point with the coordinates of the *i*-th consumer to each point in the study area:

$$D_{i,G}^{cl} = \begin{bmatrix} d_{i,G}^{cl}(1,1) & d_{i,G}^{cl}(1,2) & \cdots & d_{i,G}^{cl}(1,n) \\ d_{i,G}^{cl}(2,1) & d_{i,G}^{cl}(2,2) & \cdots & d_{i,G}^{cl}(2,n) \\ \vdots & & \ddots & \vdots \\ d_{i,G}^{cl}(k,1) & d_{i,G}^{cl}(k,2) & \cdots & d_{i,G}^{cl}(k,n) \end{bmatrix}, (9)$$

With the help of geodetic distance maps (9), a cumulative geodetic distance map is formed: $D_{i,G}^{cl} = \sum_i D_{i,G}^{cl}$.

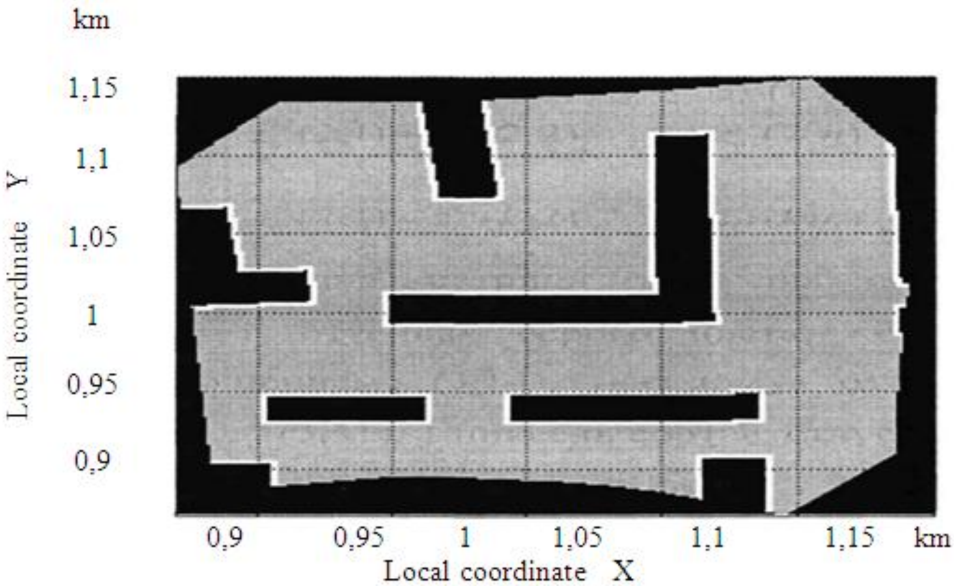

***Fig. 1.* Image of the matrix of values Z_0^{cl}.**

The most expensive areas are marked with a light shade of gray, the "Star" marker marks the minimum point as the coordinates of the optimal location of the TP.

The "Fast marching" algorithm used in the study is a discrete difference analog of the wave front algorithm. This numerical algorithm allows us to find numerical solutions to the Eykonal equation - |grad(*D*(*x*, *y*)| = *P*(*x*, *y*), here *D*(*x*, *y*) is a function of the geodesic distance. This algorithm uses the gradient descent method and resembles Deykstry algorithm for finding optimal paths on graphs.

Information on this algorithm can be found in [1, 2, 4].

To determine the elements of the cost matrix Z_0^{cl}, it is necessary to know the cost of the cable of the required cross section.

The main points related to the choice of optimal technical and economic sections of the *CL* are described in the *ПУЭ* [3] of this study.

Since the section of the low voltage network is considered in this example, in the task of choosing the optimal technical and economic section of the *CL*, we will follow the recommendations given in the regulatory documents [6-9, 12].

In accordance with the *ПУЭ* [3], cable sections with a voltage of up to 1 *kV* are selected according to the heating condition with a long rated current in normal and post emergency modes, according to the ratio (I_M). The selected cross section value is then checked for compliance with the voltage loss criterion (F_i).

The current in the line during the period of maximum power consumption is calculated according to the expression:

$$I_M = \frac{P_M}{\sqrt{3} \cdot U_n \cdot cos\varphi}, \quad (10)$$

where P_M - consumer load, U_n - rated voltage.

We believe that the correction coefficients have the following values: K_1=1; K_2=0,95; K_3=1.

The maximum permissible currents I_{perm} can be calculated according to the formula:

$$I_M = \frac{P_M}{0{,}95 \cdot \sqrt{3} \cdot U_n \cdot cos\varphi}, \quad (11)$$

The nomenclature sections selected according to the condition of heating by a long term design current are presented in *Table 1*.

Table 1. Calculated parameters of the elements of the *PS* network of the weighted Voronoi diagram №14

Parameters		Consumer 1	2	3	4	5	Cumulative parameters
Load *P*, kVt		80	84	84	64	80	412
Coordinates, m..	X_L	996	939	1042	973	1074	Assumed X_{TS} coordinate TS, m
							960/63
	Y_L	1061	1006	1095	942	943	Assumed Y_{TS} coordinate TS, m
							1006/114
Length of cable lines routes L, m.		65,8	21,5	121,3	65,8	141,1	415,5
Limit current I_{perm}, A		140	147	147	112	140	
Section F_{table} ПУЭ, mm^2		35	50	50	25	35	
Calculated cross section of $F_{\Delta U}$ for voltage loss, mm^2		24	8	45	19	50	
Recommended nomenclature value of the section F, mm^2		35	50	50	25	50	

Consider the laying of a *CL* with a voltage of 0,38 *kV* of the ***Авбг*** brand (3x70+1x16 mm^2). The enlarged cost indicators [6-8] in terms of 2021 correspond to the unit price of 3450 thousand sum./m. In places where it is necessary to open and restore the roadway, the unit price increases to 4305 thousand sum./m.

In addition, depending on the topology of the *PS* network, certain sections of the territory are more preferable for cable laying than others from a technological point of view.

According to paragraph 2.3.11 of the *ПУЭ* [3], the design and construction of the *CL* should be carried out on the basis of technical and economic calculations, taking into account the development of the network, the responsibility and purpose of the line, the nature of the route, the method of laying, cable structures, etc.

Routes for *CL* are planned taking into account the location of the *TS* and the *IDD* of *EE* consumers.

For example, routes for laying *CL* along buildings, but no closer than 0,6 m from the foundation, are more preferable, since this allows you to take advantage of the loop layout in case of an emergency. It is necessary to avoid laying *CL* under the foundations of buildings and structures. The marking of such "preferred" sections for cable laying depends on the topological and architectural features of the area under consideration and is entirely within the competence of the L_{PR}.

Taking into account the reliability factor of the network layout [4, 6, 9-14], we mark the sections along the perimeter of buildings with a width of 2 meters with a 20% preference index. All other things being equal, cable laying on sections of the marked territory is conditionally twenty percent cheaper. Consequently, in the marked zone, the unit cost of laying the cable is 3585 sum/m. for paved areas and 3285 sum/m. for uncoated areas (at the same cable price).

The growth coefficient of the cost of electrical energy is assumed to be equal: k_{wc} = 0,06.

The coefficient of reduction of multi-time costs: k_{dr} = 0,08.

Electricity price: c = 295 *sum./kW·h* (450).

Resistivity of a three core aluminum cable with a cross section: 70 mm^2 – r_0=0,43 *Ohm·km*.

The period of operation of the network: *T*=30 *year*.

For these parameter values presented in (6), the function z_0^{cl} in the case of asphalt pavement has the form shown in *Fig.1*.

Loads and their corresponding *CL* lengths are presented in *Table 1*.

Permissible voltage losses in 0,4 *kV* networks should be no more than 4-6% [4].

Since in the example under consideration the load is concentrated at the end of the *CL*, the expression for the cable section calculated by the permissible voltage loss (F_i) takes a simpler form:

$$F = \frac{A \cdot P_M \cdot L}{\Delta U_n \%}, \quad (12)$$

where *A* - the coefficient, depending on the accepted units, is determined by the reference book [11], *A*=21,9 for network 0,4 *kV*; *ΔU%* - voltage loss, expressed as a percentage, in the example under consideration *ΔU%*=5%; *L* - length *CL*.

If the cross-section of the conductor selected according to the heating condition with a long design current turns out to be less than the cross-section according to the permissible voltage loss, then for this load, a cross-section from the nomenclature series is selected in accordance with the criterion for permissible voltage loss. Next, the matrix of unit costs z_0^{cl} is recalculated in accordance with the selected section and the map of geodetic distances is recalculated for the load under consideration and the cumulative map. The coordinates of the minimum point of the cumulative distance map are determined and the optimal trajectories for laying the *CL* are calculated anew. This procedure continues until the obtained sections meet the criteria defined in the *ПУЭ* [3].

Table 1. presents calculated data for the region under consideration, obtained using digital image processing algorithms taking into account load heterogeneity based on Vorono diagrams.

Conclusion. The determination of the *TS* responsibility zones using algorithms based on weighted Vorono diagrams made it possible to take into account the heterogeneity of the load density when calculating the parameters of the *PS* elements and redistribute the electricity consumers across the *TS* responsibility zones in such a way that the coefficient of variation of the load density decreases.

The use of the expression of relative reduced costs in a dimensionless form as a *Z* makes it possible to take into account the prospective growth of the load and obtain, independent of the economic situation, the results of optimization procedures.

The use of expensive matrices in the form of grayscale images and maps of geodetic distances allows us to take into account the local features of the region of planning and/or reconstruction of the *PS* network, which reduces the uncertainty and unreliability of initial data and apply digital image processing algorithms in the tasks of determining the optimal parameters of elements of urban *PS* networks.

The generalized algorithm for determining the optimal technical and economic parameters of the elements of the *PS*, taking into account the heterogeneity of the load density based on Vorono diagrams, implemented in machine code, allows you to get recommendations on the parameters of the elements of the *PS* networks, which can be taken as a basis for making decisions of the L.

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