Determination of the service area and location of transformer substations in the city power supply system

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Abstract. The article proposes a theoretically based approach to determining the service areas and location of transformer substations (TS) in the case depending on the intensity of the electric load based on the area specified in the city power supply system. Rational use of service areas and determination of the optimal area by location will help regulate the city's power supply. As a result of the scientific approach in the article, the targeted use of a transformer substation in the municipal power supply system will achieve orderly development in the city, as well as a reduction in the waste of electricity in distribution power networks.

1 Introduction

Currently, all elements of the power supply system of existing cities are components of the regional or state energy system. Such systems have multiple voltage standards scale level networks and are constantly evolving. In this case, it is important to make a decision on the basis of a timely scientific approach to determining the transformer substations and their service areas and location, which are the main element of the city power supply system. Each city power supply system has a certain hierarchy of voltages. In the substations of the municipal power supply system, as a rule, 220/35, 110/35, 110/10, 35/10, 10/0,4 kV transformers of the voltage level are used.

2 Voltage and electric load density gradation in the city electric networks

In city power supply, the total electric load is formed by the electricity of existing consumer groups. These generated electrical loads should be provided uninterrupted by transformer substations within the city power supply system. The optimal power of transformers in substations, which depends on the different voltage level in the urban area, depends on the electrical load density of the area. The electrical load density in the individual areas of the city obtained differs from the average load density in the city. The value of the electric load density depends on the specifics of the territorial construction, the number of floors of the premises located, the degree of electrification and the value of the voltage in the connection of consumers to TP. The electrical load density at each voltage level is determined by the total load at the previous network level of consumers and the additional load at the level under consideration. As a result, the electrical load density in

hierarchy transition networks corresponding to electrical network voltages is determined by networks as follows [1, 10-15, 18-23, 9]:

$$\sigma_0 = \frac{S_{\Sigma 0,4}}{F_{city}} \quad (1)$$

$$\sigma_1 = \frac{S_{\Sigma 10-35}}{F_{city}} \quad (2)$$

$$\sigma_2 = \frac{S_{\Sigma 35-110}}{F_{city}} \quad (3)$$

$$\sigma_3 = \frac{S_{\Sigma 110-220}}{F_{city}} \quad (4)$$

where, $S_{\Sigma 0,4}$ – power load of consumers on the transformer substation 0.4 kV voltage tire, σ_0 – electrical load density;

$S_{\Sigma 10-35}$ – power load of consumers on a transformer substation 10 or 35 kV voltage tire, σ_1 – electrical load density;

$S_{\Sigma 35-110}$ – power load of consumers on a transformer substation 35 or 110 kV voltage tire, σ_2 – electrical load density;

$S_{\Sigma 110-220}$ – electrical load of consumers on a transformer substation 110 or 220 kV voltage tire, σ_3 – electrical load density.

The voltage by voltage rating of all transformer substations providing the city area depends on the description of consumers of electricity of individual power at each stage. Electricity consumers are considered one or three phase in terms of reliability and rated power, voltage of the power supply. On the territory of the city, a voltage of 220 kV is used, mainly in electrical networks coming from the power plant, if we see the example of the city of Tashkent. By the sequence stage, it is divided into electrical networks with a voltage of 110, 35, 10, 0.4 kV. On the territory of Uzbekistan, networks with a voltage of 330, 20, 6 kV are not used for city power supply. Transformer substations

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also use power transformers suitable for existing electrical network voltages [2-4].

The hierarchy of voltage and electric load density in the city distribution electrical networks is schematically shown in Fig. 1.
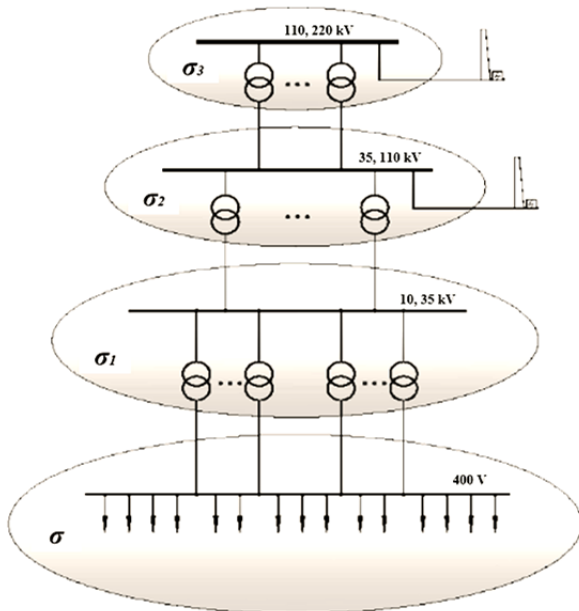

Fig. 1. Voltage and electric load density gradation in the city electric networks.

From the above expressions 1, 2, 3, 4 it follows that the actual electric load density at each voltage level varies due to different regions and factors simultaneously influencing the maximum electrical load of transformers in TS [5, 16-24].

If the electrical loads generated by consumers and the area of the city (or part of it) allocated for the building are known, the average electrical load density at the total voltage level in this city (or part of it) is determined as follows:

$$\sigma_{i.} = \frac{S_{city}}{F_{city}} \qquad (5)$$

where, σ_i – i - average electrical load density for a voltage level electrical network, [MVA/km^2];

S_{city} – the total electrical load of city electrical networks (or part of it) at a certain voltage level in the city power supply system, [MVA];

F_{city} – city area (or part of it) allocated for the construction of a residential or public building, [km^2].

In the general case, the total electrical load of the city (or part) at a certain voltage level of the municipal power supply system is determined as follows:

$$S_{city} = k_{TS.i} \cdot \sum_{i=1}^{n_{TS}} S_{TS.i} = k_{TS.i} \cdot \sum_{i=1}^{n_{TS}} n_i \cdot \beta_i \cdot S_{nom.i} \qquad (6)$$

where, $S_{TS.i}$ – i - electrical load of transformer substation, [MVA];

$k_{TS.i}$ – coefficient taking into account the simultaneous maximum load of transformers depending on the number of TS in the network at a given suitable voltage level;

n_i – number of transformers in substation;

β_i – load coefficient of the i - transformer in the substation;

$S_{nom.i}$ – i - rated power of substation transformers, [MVA];

n_{TS} – number of transformer substations in an urban area (or part thereof).

3 Determination of the service area of transformer substation

The service area and time of transformer substations located on the territory of the city power supply system depend on the type of consumers located in the area, the floor of the premises, the location of the electrical load depends on the geometric description. On the territory of the city, electricity consumers form an electric load in a vertical position. Taking into account this, the issue of determining the service area by the geometric location of the transformer substation is considered relevant. Determining the geometric area in the optimal position has a great influence on the development of urban planning and city power supply. By determining the limit optimal area of the transformer substation, it is possible to achieve a reduction in the length of low voltage electrical networks, as well as a reduction in the cost of waste electricity [6-10].

To provide qualitative electricity supply for all the consumers of a city they are to be rationally distributed among separate transformer substations according to their service area. The service area of each separate substation is defined by the load density in this area and the TS load, which, in turn, depends on the rated power of a corresponding transformer, the number of transformers at the substation and the load factor:

$$F_{city} = \frac{s_{TS.i}}{\sigma_{TS.i}} = \frac{n_i \cdot \beta_i \cdot S_{nom.i}}{\sigma_{TS.i}} \qquad (7)$$

where, $\sigma_{TS.i}$ - is the load density in the service area of the i - substation.

In the absence of a technical solution or a single approach to the design and modelling of the elements of an city power supply system, it can have complex geometric shapes or schemes that differ for each substation by area. This makes it difficult to choose a place for new substations and purposefully develop a power supply scheme. Therefore, by the rules of city planning regulations, it is not allowed to connect additional loads to the city area or build a substation.

When determining the service area of the transformer substation can be designed and modeled with geometric shapes. For example, in geometry there are circle, square, regular six, eight corners, etc. The most convenient model is the hexagon. This makes it possible to cover almost any shaped area of the building in a regular order. This model of the transformer substation service sector can be selected as the only template in the design work. Design and modelling in such a way is considered useful in making decisions on the development of urban distribution electrical networks. It is conditionally accepted that the transformer substation should be in the center of the hexagon (in the practical

case, the area should not fall beyond the boundaries of the hexagon).

Figures 2, 3 describe the template in the sample case for the service area of various rated voltage transformer substations to be placed in the city area, as well as the designable ideal view of the service. Through these presented images, a vision is generated by the service area [1, 8, 13].
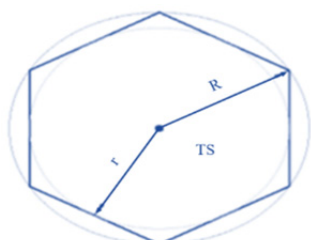

Fig. 2. The model template for the service area of a transformer substation.
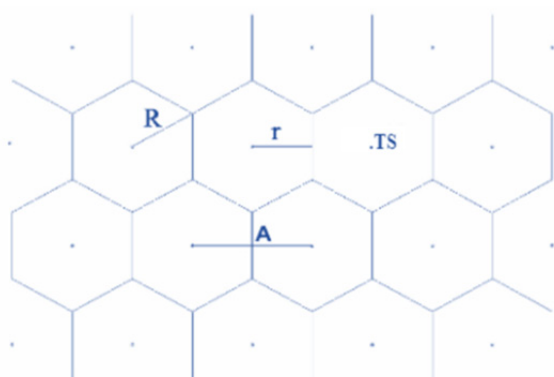

Fig. 3. An ideal model of service areas of transformer substations.

Between the basic geometrical sizes of the models shown in Figs. 2 and 3 the following relationships exist:

$$F_{TS} = 3\sin\left(\frac{\pi}{3}\right) \cdot R^2 = 2,6 \cdot R^2 = 3,46 \cdot r^2 \quad (8)$$

$$R = 0,62 \cdot \sqrt{F_{TS}} \quad (9)$$

$$r = 0,54 \cdot \sqrt{F_{TS}} \quad (10)$$

$$A = 2 \cdot r = 1,1 \cdot \sqrt{F_{TS}} \quad (11)$$

where, R - the radius of the circle described around the hexagon (also the side of a hexagon and the radius of TS service area);

r - the radius of the circle described inside the hexagon;

A - the theoretically minimal distance between the neighboring substations.

Considering (7) and (8-11), the following relationships are valid between the basic sizes of the geometrical model-template of TS service area, its load density and the technical parameters of the existing or future TSs [1, 9-10]:

$$F_{TS} = 2,6 \cdot R^2 = \frac{n_i \cdot \beta_i \cdot S_{nom.i}}{\sigma} \quad (12)$$

$$R = 0,62 \cdot \sqrt{\frac{n_i \cdot \beta_i \cdot S_{nom.i}}{\sigma}} \quad (13)$$

$$r = 0,54 \cdot \sqrt{\frac{n_i \cdot \beta_i \cdot S_{nom.i}}{\sigma}} \quad (14)$$

$$A = 2 \cdot r = 1,1 \cdot \sqrt{\frac{n_i \cdot \beta_i \cdot S_{nom.i}}{\sigma}} \quad (15)$$

Considering that some TS service areas under particular conditions of the city building can overlap one another, it is necessary to verify fulfilment of the condition:

$$F_{city} \leq k_{rc} \cdot \sum_{i=1}^{n_{TS}} F_{TS.i} \quad (16)$$

where, $F_{TS.i}$ - the service area of the i - substation, km^2;

k_{rc} - the accepted recovering factor of service areas.

On the assumption of identical installed rated power, load factors and service area of the TS transformers, the average load density in the city (or its part) in view of (5), (6) and (12) will be:

$$\sigma_{city} = \frac{k_{TS.i} \Sigma_{i=1}^{n_{TS}} S_{TS.i}}{k_{pkl} \cdot F_{TS.i} \cdot n_{TS}} = \frac{k_{TS.i} \Sigma_{i=1}^{n_{TS}} n_i \cdot \beta_i \cdot S_{nom.i}}{k_{pkl} \cdot F_{TS.i} \cdot n_{TS}} \quad (17)$$

The average load density in the city (or its part) at different capacities of transformer substations can be defined as:

$$\sigma_{city} = \frac{k_{TS.i} \cdot (S_{TS.1} + S_{TS.2} + \cdots + S_{TS.i})}{k_{cov} \cdot (F_{TS.1} + F_{TS.2} + \cdots + F_{TS.i})} \quad (18)$$

The resulting expressions of the proposed nature of all the expressions considered transformer are determined by the value of the high voltage. The values obtained expression are quoted in Table 1 below through the expression obtained on low voltage.

Table 1. Results determined by the value of the electric charge density at the level of one voltage (on the example of Tashkent city).

S_{SS}, MVA	2x40 (skirting schemes)			
σ, MVA/km^2	2	4	8	12
$S_{TS,}$ kVA	320	454	580	658
F_{city}, km^2	0,16	0,12	0,07	0,06
R, km	0,248	0,215	0,164	0,151
S_{SS}, MVA	2x40 (two trunk schemes)			
σ, MVA/km^2	8	16	24	32
$S_{TS,}$ kVA	1009	1435	1763	2041
F_{city}, km^2	0,126	0,09	0,074	0,064
R, km	0,22	0,186	0169	0,157

4 Determination the location of transformer substations

In the city power supply system, the number and nominal full capacities of transformers in the transformer substation are determined by state all union standard. After the calculation is carried out, the installation of each transformer substation over a small non area of the

transfomer substations is determined by the coordinates of the center for conditional loads (X_0, Y_0) through this expression:

$$X_0 = \frac{P_1 \cdot X_1 + P_2 \cdot X_2 + \cdots + P_i \cdot X_i}{P_1 + P_2 + \cdots + P_i} \qquad (19)$$

$$Y_0 = \frac{P_1 \cdot Y_1 + P_2 \cdot Y_2 + \cdots + P_i \cdot Y_i}{P_1 + P_2 + \cdots + P_i} \qquad (20)$$

X_i, Y_i – consumer coordinate in the area, [cm]; P_i - the calculated asset load of the consumer in the area, [kW].

The coordinates of TS determined by area may not coincide with the calculated points. In this case, the conditional loading center can fall over the building or in the direction of movement. In this case, the center of conditional loads can be moved to a point close to consumers with a large capacity [11-16, 20, 22, 24].

Let's explain using an example for a small area on determining the optimal location coordinate of TS in the city power supply system. Information about the consumer capacities of 20 consumers located in the resulting area, as well as their location coordinates, is presented in Table 2.

Table 2. An example of calculating the optimal configuration of an urban district distribution electrical network

Buildings №	Location coordinates		Computing power, kVA
	X	y	
1	75	315	40
2	75	150	30
3	105	75	40
4	105	225	35
5	130	275	35
6	180	315	40
7	275	280	30
8	160	150	35
9	180	75	50
10	230	275	35
11	250	180	40
12	220	100	70
13	300	225	30
14	300	130	25
15	330	315	35
16	350	205	40
17	360	170	50
18	365	250	70
19	410	170	30
20	410	100	20

Based on the initial data in Table 2, from expressions (19) and (20), the transformer by area determines the location coordinate. The territory is conditionally allocated to 2 TS and is provided with lines in the form in Figure 4.
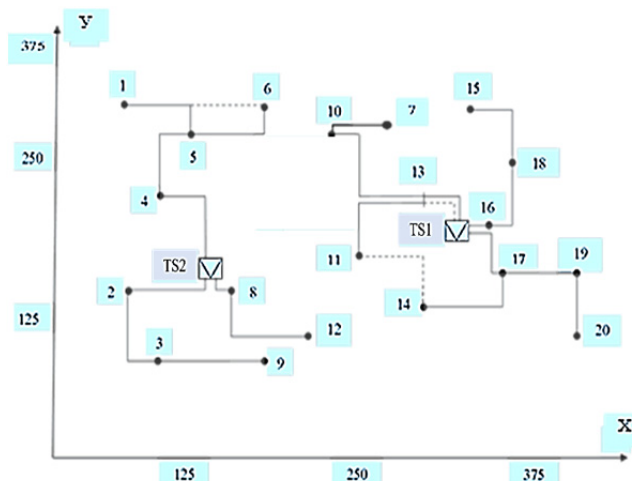

Fig. 4. Calculation of the optimal configuration of the distribution power network of the city district.

It can be seen from Figure 4 that when supplying regions, lines should be ensured that they do not intersect and do not back down. The consumers allocated for the transformer substation as well as their consumption capacities, location coordinates are shown in Table 3.

Table 3. The optimal location of each TS is the sum of the relays and capacities

TS1	X = 315	Y = 200	405
TS2	X = 150	Y = 170	375

Length of lines up to 1000 V:
- Within TS1 387 m (7, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20);
- Within TS2 313 m (1, 2, 3, 4, 5, 6, 8, 9, 12);

Loading each line 135, 125, 145 kVA (TS1), 150, 120, 105 кВА (TS2); Distance between TS 167 m.

The location coordinate of TPS for consumers in networks with a voltage of up to 1000 V over the resulting area, as well as the location of power supply lines, was cited [21-26, 28, 30, 31,].

5 Conclusion

In the city power supply system, theoretical foundations for determining service areas and their radii for transformer substations of different voltage levels were developed. with the help of the developed bases, a hierarchy of electrical load density of TS service fields was proposed in accordance with the hierarchy of voltage in electrical networks. For the rational placement of TS in the territory of the city power supply, models and templates were developed based on various geometric shapes. The dependence of TS service areas and their radii on the electrical load density in the service sector for TS with two transformers 220/35-110 kV, 110/10-35, 35/10 and 10/0,4 kV was determined. Based on the consumer power and location coordinates of the consumers received by the territory, the theoretical concepts of the location of the TS and the placement of power supply lines were reasonably explained using a practical example. This method, developed, will be able

to reduce the waste of resources and electricity in city electricity supply and will have a positive effect on the development and expansion trend of cities.

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