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DETERMINATION OF SERVICE AREAS OF URBAN TRANSFORMER SUBSTATIONS AND DISTRIBUTION USING GEOMETRICAL TEMPLATES

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In the work, a general and theoretically substantiated approach is proposed for the arrangement and determination of service areas for the future transformer substations (TSs). The modelling of TS service area has been performed, with geometrical templates designed to arrange TSs in the city building territory. The sizes of templates have been obtained depending on the TS capacity and load density in TS service area. The geometrical templates are to help in TS arrangement in view of rational use of the city territory and to re-arrange the existing stations for the reconstruction time. As a result, the urban power supply system will develop not chaotically but in a purposeful manner.

Key words: *transformer substation, modelling, service area, service radius.*

1. INTRODUCTION

The power supply system (PSS) of a major city is, as a rule, the component of a regional or a state power system. Such a system has networks of several voltage levels, and is continuously developing. It is very important to develop the system rationally and to take timely correct decisions as to the formation of the whole system and of its separate parts. Every urban PSS is formed historically, with a certain hierarchy of voltages in its networks. As a rule, in the urban PSSs the voltage levels of 400 (330)/110 (220)/10 (20) kV are used.

2. HIERARCHY OF VOLTAGES AND LOAD DENSITIES IN THE URBAN POWER SUPPLY SYSTEMS

The total electric load of a city is formed by the electric power of various groups of consumers. This load should be provided by the necessary total power of the urban transformer substations (TSs). The optimum capacity of the urban TSs in the networks of different voltage depends on the load density in the city and in its separate areas. The load densities in separate areas of a city differ from the average load density in this city and, in turn, depend on the specifics of territorial building, its typical number of storeys, the level of electrification, and the voltage level at the consumers' connections to the PSS. The load density on each voltage level is determined by the total load of consumers on the previous level and the additional load on the level under consideration. As a result, the load densities in the networks of a PSS form the hierarchy corresponding to that of network voltages. The average densities of loads on each voltage level in a 330 (400) /110/10–20/0.4 kV power supply system, beginning from the lowest, are:

$$\sigma_0 = \frac{S_{\Sigma\, 0,4}}{\Pi_{city}}; \qquad (1)$$

$$\sigma_1 = \frac{S_{\Sigma\, 10-20}}{\Pi_{city}}; \qquad (2)$$

$$\sigma_2 = \frac{S_{\Sigma\, 110}}{\Pi_{city}}; \qquad (3)$$

$$\sigma_3 = \frac{S_{\Sigma\, 330(400)}}{\Pi_{city}}, \qquad (4)$$

where $S_{\Sigma\, 0,4}$, σ_0 is the total load of consumers and the load density on the 0.4 kV busbars of transformer substations;

$S_{\Sigma\, 10-20}$, σ_1 is the same for the 10–20 kV busbars of TSs;

$S_{\Sigma\, 110}$, σ_2 – the same for the 110 kV busbars of TSs;

$S_{\Sigma\, 330(400)}$, σ_3 – the same for the 330 (400) кV busbars of TSs;

Π_{city} is the city territory suitable for building.

The following relations between the load densities exist for different voltage levels:

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(5)

where $k_{o,1}$ is a factor of simultaneity for the maximum load of 10–20/0.4 kV transformers depending on the TS number in a 10–20 kV network;

$k_{o,2}$ is a factor of simultaneity for the maximum load of 110–10/20 kV transformers depending on the TS number in a 110 kV network;

$k_{o,3}$ is a factor of a simultaneity for the maximum load of 330 (400)/ 110 kV transformers depending on the TS number in a 330 kV network.

The hierarchy of voltages and load densities in urban networks is presented schematically in Fig. 1.

From (1–5) it follows that the actual load densities on each voltage level are differing because of different TS numbers and factors of simultaneity for the maximum load of transformers in the networks of a PSS.

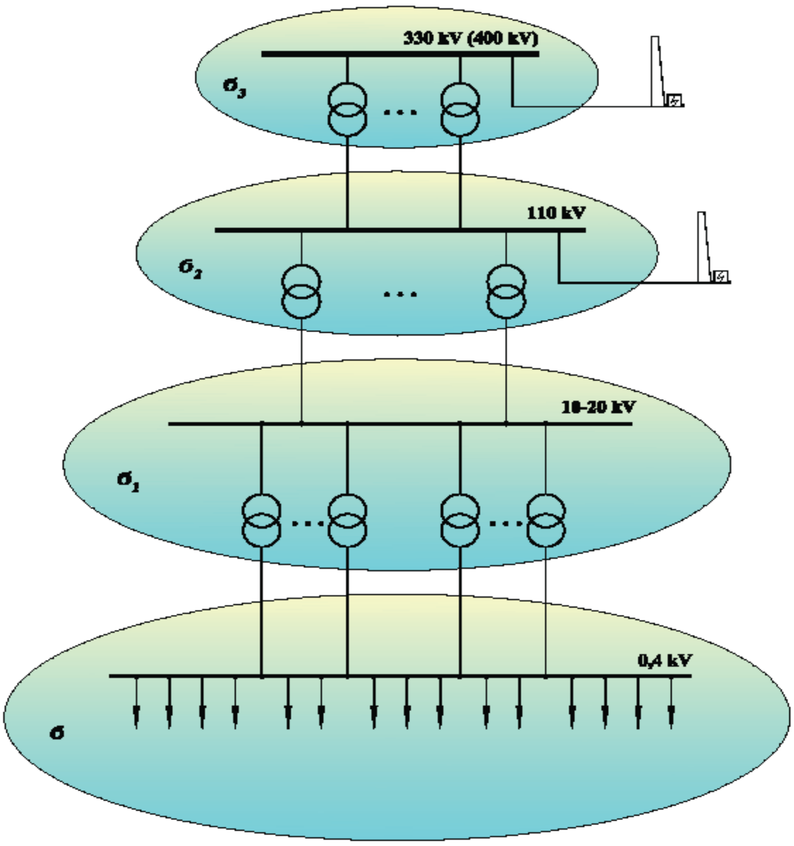

Fig.1. The hierarchy of voltages and load densities in the urban electric networks.

If the consumers' loads and the territory of a city (or its part) allocated for building are known, the average load density in this city (or its part) on a given voltage level in the general form is:

$$\sigma_{av,i} = \frac{S_{city}}{\Pi_{city}} \quad , \qquad (6)$$

where $\sigma_{av,i}$ is the average load density in a network on the *i*-th voltage level, MVA/km^2;

S_{city} is the total electrical load of the city (or its part) on a given voltage level in the PSS, MVA;

Π_{city} is the territory of the city (or its part) allocated for building, km^2.

The total electrical load of the city (or its part) on a given voltage level of the PSS in the general form will be:

$$S_{city} = k_{oi,TS} \cdot \sum_{i=1}^{n_{TS}} S_{TS,i} = k_{oi,TS} \cdot \sum_{i=1}^{n_{TS}} n_i \beta_i S_{nom,i} \ , \qquad (7)$$

where $S_{TS,i}$ is the load of the *i*-th transformer substation, MVA;

$k_{o\,i,TS}$	is the factor of simultaneity for the maximum load of transformers depending on the TS number in the network on a given voltage level;
n_i	is the number of transformers in the substation;
β_i	is the load factor of the *i*-th transformer in the substation;
$S_{nom,i}$	is the rated power of transformers in the *i*-th substation, MVA;
n_{TS}	is the number of transformer substations in the city (or its part).

3. MODELLING OF THE SERVICE AREA OF A TRANSFORMER SUBSTATION

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:

$$\Pi_{TS,i} = \frac{S_{TS,i}}{\sigma_{TS,i}} = \frac{n_i\,\beta_i\,S_{nom,i}}{\sigma_{TS,i}}\,, \tag{8}$$

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

In the absence of a uniform approach to the modelling, these areas can have complicated geometrical forms sometimes differing for each substation. This makes difficult the choice of the location for new substations and the purposeful development of the electricity supply scheme.

The service area of a transformer substation can be modelled by diversified geometrical figures: a circle, a square, a regular hexagon, etc.. The most convenient model is a hexagon, which enables filling practically any shape territory of building in regular order (Figs. 2, 3). This model of TS service area is chosen in the work as a uniform model-template that will be useful at the decision-making concerning the development of city networks. It is conditionally accepted that the transformer substation should be at the hexagon centre (in real circumstances it should not fall outside the borders of the hexagon).

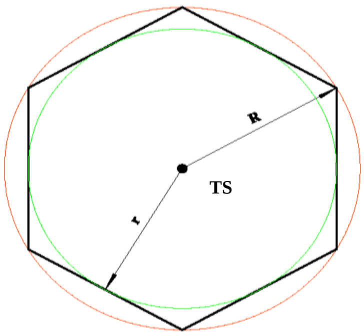

Fig. 2. The model-template for the service area of a transformer substation.

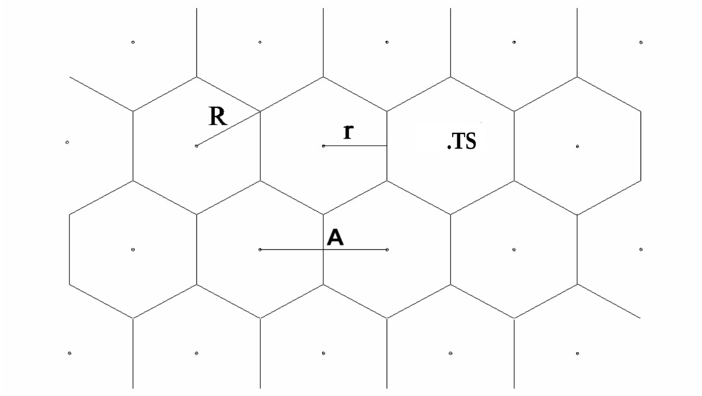

Fig. 3. An ideal model of service areas of transformer substations.

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

$$\Pi_{TS} = 3\sin\left(\frac{\pi}{3}\right)\cdot R^2 = 2.6\cdot R^2 = 3.46\cdot r^2 ; \tag{9}$$

$$R = 0.62 \cdot\sqrt{\Pi_{TS}} ; \tag{10}$$

$$r = 0.54\cdot\sqrt{\Pi_{TS}} ; \tag{11}$$

$$A = 2\ r = 1.1\cdot\sqrt{\Pi_{TS}} , \tag{12}$$

where R is the radius of the circle described around the hexagon (also the side of a hexagon and the radius of TS service area);
r is the radius of the circle described inside the hexagon;
A is the theoretically minimal distance between the neighbouring sub-stations.

Considering (8) and (9–12), 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:

$$\Pi_{TS} = 2.6\cdot R^2 = \frac{n_i\ \beta_i\ S_{nom,i}}{\sigma_i} ; \tag{13}$$

$$R = 0.62\cdot\sqrt{\frac{n_i\,\beta_i\ S_{nom,\,i}}{\sigma_i}} ; \tag{14}$$

$$r = 0.54\cdot\sqrt{\frac{n_i\ \beta_i\ S_{nom,i}}{\sigma_i}} , \tag{15}$$

$$A = 1.1\cdot\sqrt{\frac{n_i\ \beta_i\ S_{nom,i}}{\sigma_i}} . \tag{16}$$

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:

$$\Pi_{city} \le k_{rc} \cdot \sum_{i=1}^{n_{TA}} \Pi_{TS,i} \quad , \tag{17}$$

where $\Pi_{TS,i}$ is the service area of the *i*-th substation, km^2;

k_{rc} is 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 (6), (7) and (13) will be:

$$\sigma_{av.sity} = \frac{k_{o,TS} \cdot \sum_{i=1}^{n_{TS}} S_{TS,i}}{k_{pkl} \cdot \Pi_{TS} \cdot n_{TS}} = \frac{k_{o,TS}\, n \beta S_{nom}\, n_{TS}}{k_{pkl} \cdot \Pi_{TS} \cdot n_{TS}} \quad . \tag{18}$$

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

$$\sigma_{av.sity} = \frac{k_{o,TS} \cdot \left(S_{TS,1} + S_{TS,2} + \ldots + S_{TS,i}\right)}{k_{\mathrm{cov}} \cdot (\Pi_{TS,1} + \Pi_{TS,2} + \ldots + \Pi_{TS,i})} =$$

$$= \frac{k_{o,TS} \sum_{i=1}^{n_{TS}} S_{TS,i}}{k_{\mathrm{cov}} \cdot \sum_{i=1}^{n_{TS}} \Pi_{TS,i}} = \frac{k_{o,TS} \sum_{i=1}^{n_{TS}} n_i \beta_i S_{nom,i}}{k_{\mathrm{cov}} \cdot \sum_{i=1}^{n_{TS}} \Pi_{TS,i}} . \tag{19}$$

4. DEPENDENCES OF THE TS SERVICE AREA AND ITS RADIUS ON THE LOAD DENSITY

The adopted model of the TS service area allows designing templates (of hexagonal shape) of such an area for substations of any voltage. According to the adopted model, we can determine the maximum admissible and the actual service areas and their radiuses.

To solve this task it is necessary to have information on:

- the load density in different districts of the city;
- the installed or designed rated power of the transformer (optimal at the existing load density or accepted based on the operating experience);
- the number of transformers at the TSs;
- actual or accepted admissible load factor of transformers.

The accepted admissible load factor of transformers should be economically justified (without unreasonable excess of the installed power in a network) and allowing the overload level admissible for transformers in compliance with specifications IEC 354-91. Usually, a new transformer substation is able to reach the planned estimated load not earlier than five years after the beginning of operation. It is desirable after reaching the estimated load to schedule some reserve of the TS installed load for a definite time without TS and network reconstruction.

The accepted admissible load factor of transformers enables us to check whether the actual service area of the existing substation corresponds to the maximum admissible service area and to draw conclusions about the necessity of re-structuring the old TSs or constructing a new one. For new prospective substations it is possible to calculate both the maximum permissible and the real (at the real load factor) service areas as well as the TS radiuses. The difference between the maximum permissible and the real service areas allows estimation of the reserve for the load increase at a future TS.

The results of calculation are exemplified by Table 1, where the data on the service areas and radiuses of 110 kV two-transformer TSs depending on the load density are presented. The admissible load factor of transformers in the normal mode is accepted to be β_b = 0.5 for two-transformer substations (typical of the Riga city networks). Such factor allows holding a permanent load for the second transformer no higher than the rated load in the case of switching-off the first transformer. This suggestion, however, has not yet been well-founded.

At the accepted admissible load factor the maximum admissible TS service area and its radius are obtained. The TS service area and its radius at different values of load factor can be calculated by expressions (13), (14).

Table 1

Service area Π_{TS} and its radius R for 110 кV two-transformer substations depending on load density σ_2

	β_b = 0.5									
σ_2, MVA/km^2	Π_{TS}, km^2					R, km				
	n x S_{nom}					n x S_{nom}				
	2x16	2x25	2x32	2x40	2x63	2x16	2x25	2x32	2x40	2x63
3	5.33	8.33	10.67	13.33	21.35	1.43	1.79	2.03	2.27	2.87
5	3.20	5.00	6.40	8.00	12.81	1.11	1.39	1.57	1.76	2.22
8	2.00	3.13	4.00	5.00	8.01	0.88	1.10	1.24	1.39	1.76
10	1.60	2.50	3.20	4.00	6.41	0.79	0.98	1.11	1.24	1.57
13	1.23	1.92	2.46	3.08	4.93	0.69	0.86	0.97	1.09	1.38
15	1.07	1.67	2.13	2.67	4.27	0.64	0.80	0.91	1.01	1.28
17	0.94	1.47	1.88	2.35	3.77	0.60	0.75	0.85	0.95	1.20
20	0.80	1.25	1.60	2.00	3.20	0.56	0.69	0.79	0.88	1.11
23	0.70	1.09	1.39	1.74	2.79	0.52	0.65	0.73	0.82	1.04
25	0.64	1.00	1.28	1.60	2.56	0.50	0.62	0.70	0.79	0.99
27	0.59	0.93	1.19	1.48	2.37	0.48	0.60	0.68	0.76	0.96
30	0.53	0.83	1.07	1.33	2.14	0.45	0.57	0.64	0.72	0.91
33	0.49	0.76	0.97	1.21	1.94	0.43	0.54	0.61	0.68	0.86
36	0.44	0.69	0.89	1.11	1.78	0.41	0.52	0.59	0.65	0.83

ΠIn Figs. 4–7, the dependences of service area Π_{TS} for 110/10–20 kV and 10–20/0.4 kV transformer substations and service radius R on the load densities at corresponding voltage levels are shown.

The obtained analytical expressions (13, 14), the tabulated results of calculations and the graphic dependences (Figs. 4–7) made it possible to determine specific features of the TS service areas and its radiuses.

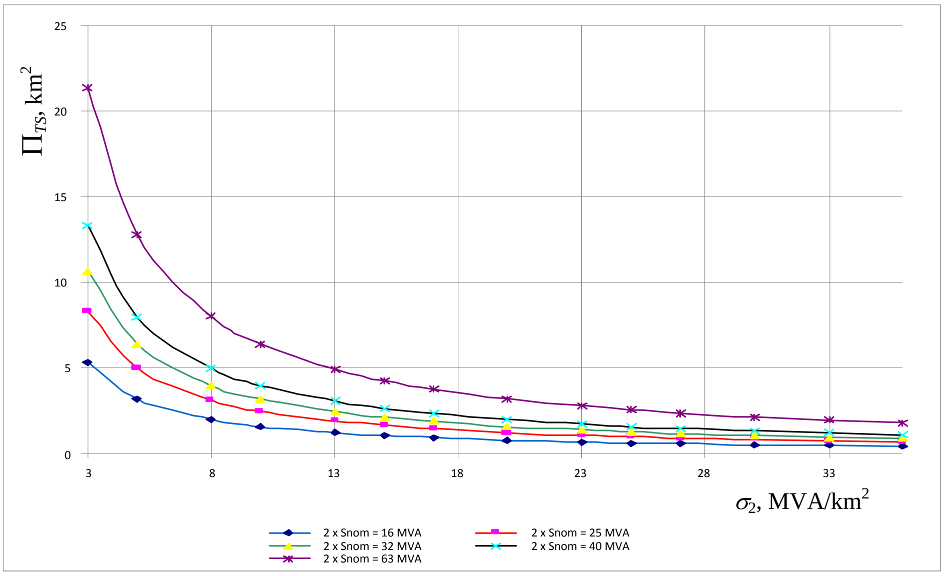

Fig. 4. TS service area Π_{TS} *vs.* load density σ_2 for 110/10–20 kV two-transformer substations.

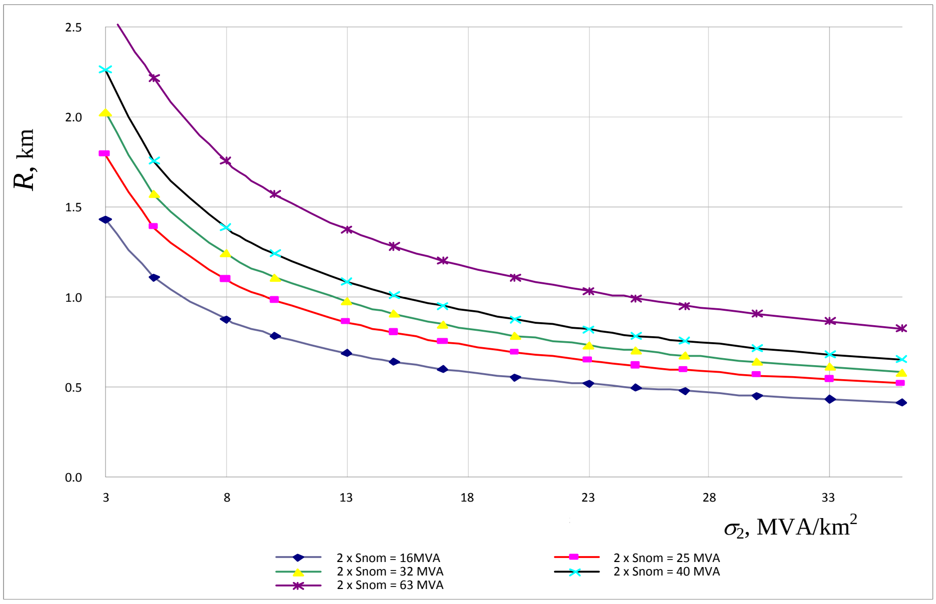

Fig. 5. Radius R of TS service area *vs.* load density σ_2 for 110/10–20 kV two-transformer substations.

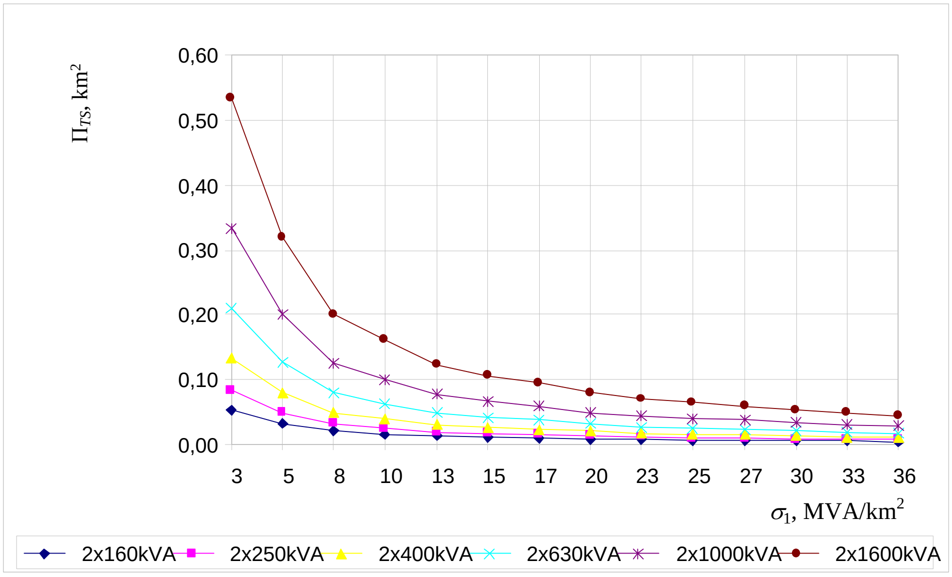

Fig. 6. TS service area Π_{TS} *vs.* load density σ_1
for 110/10–20 kV two-transformer substations.

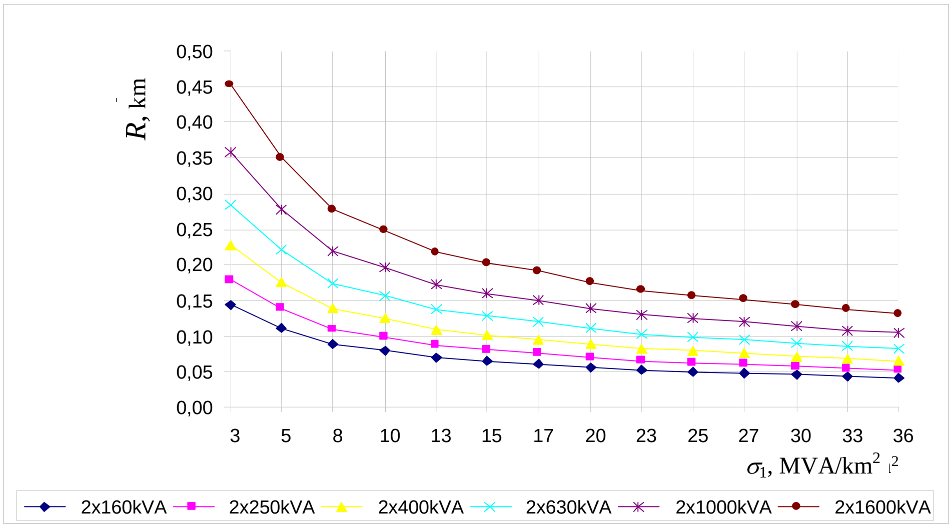

Fig. 7. Radius R of TS service area *vs.* load density σ_1
for 110/10–20 kV two-transformer substations.

The TS service area varies in direct proportion to its load (Figs. 4, 6) at a constant load density in this area, and in inverse proportion to the load density in this area (Figs. 4, 6) at a constant TS load.

The TS service area remains constant if the TS load varies proportionally to the load density in this area.

When analyzing expression (14) it is seen that the square of radius of TS service area varies in direct proportion to the TS load at a constant load density in this area.

The square of radius of TS service area varies in inverse proportion to the load density in this area (Figs. 5, 7) at a constant TS load.

The square of radius of TS service area remains constant if the TS load varies proportionally to the load density in this area.

The proposed method of using templates (hexagons) makes it possible to determine whether the distribution of existing substations respond to the concept of the work and to make a decision as to the renovation of a substation (by replacing a transformer or installing an additional one) or the construction of a new one. The method facilitates and systematizes the arrangement of TSs to be built in the city territory at development of networks.

For arrangement of templates on the city map (or its part) the geometrical sizes of templates can be determined by expressions (13–15). The templates are plotted at the places reserved in the city for transformer substations, or, whenever possible, in the centres of new loads. Using the calculation program EXCEL and the graphic program AUTOCAD it is possible to automate the process of arranging the service areas on the city's map. The developed method allows making the substantiated decisions on the development of networks at the initial design levels in the conditions of incompleteness of the primary information.

5. CONCLUSIONS

1. The theoretical basis has been developed for determination of service areas and their radiuses for urban transformer substations of different voltages.
2. The hierarchy for load densities of TS service areas according to the hierarchy of voltages in networks is proposed.
3. Geometrical models and templates of hexagonal shape have been worked out for rational arrangement of TSs in the urban territory.
4. Dependences of TS service areas and their radiuses on the load density in the service area for 110/10–20 kV and 10–20/0.4 kV two-transformer TSs are found out.
5. The developed method allows the substantiated and proved decisions on the development of networks to be made at the initial design levels in the conditions of incompleteness of the primary information.

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PILSĒTAS TRANSFORMATORU APAKŠSTACIJU APKALPES ZONU NOTEIKŠANA UN IZVIETOJUMS AR ĢEOMETRISKO ŠABLONU PALĪDZĪBU

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K o p s a v i l k u m s

Darbā piedāvāta vienotā un teorētiski pamatota pieeja jauno apakšstaciju izvietojuma izvēlei un apkalpes zonas noteikšanai. Uzdevuma risināšanai veikta apakšstaciju apkalpes zonu modelēšana. Transformatoru apakšstacijas apkalpes zona modelēta ar pareizo sešstūri. Šis modelis dod iespēju aizpildīt praktiski jebkuras formas apbūves rajona laukumu. Noteikti transformatoru apakšstacijas apkalpes zonu izmēri, kuri ir atkarīgi no transformatoru apakšstacijas slodzes un slodzes blīvuma apkalpes zonā. Slodzes blīvumi atsevišķos pilsētas rajonos, mikrorajonos vai apakšstaciju apkalpes zonās atšķiras no vidējā lieluma pilsētā ievērojamās robežās atkarībā no apbūves veida, apbūves stāvu skaita, sadzīves elektrificēšanas līmeņa, patērētāju pieslēgšanas vietas (sprieguma pakāpes) elektroapgādes sistēmā. Faktiski slodzes blīvumi katrai sprieguma pakāpei ir dažādi, veicot slodzes blīvuma hierarhiju saskaņā ar tīklu spriegumu hierarhiju. Spriegumu un slodzes blīvuma hierarhija attēlota grafiskā veidā un teorētiski analizētas slodzes blīvumu sakarības starp dažādām pakāpēm. Iegūtas apkalpes zonu un to rādiusu atkarības no slodzes blīvuma 110/10–20 kV un 10–20/0.4 kV transformatoru apakšstacijām.

Pieņemtais transformatoru apakšstaciju apkalpes zonas modelis un iegūtās matemātiskās sakarības starp modeļa pamatizmēriem dod iespēju izstrādāt apakšstaciju apkalpes zonas šablonus sešstūra veidā. Ar ģeometriskiem šabloniem, zinot optimālo vai pieņemto transformatoru jaudu, var racionāli sadalīt pilsētas apbūves teritoriju starp transformatoru apakšstacijām.

Ģeometriskos šablonus var izmantot kā perspektīvo apakšstaciju racionālam izvietojumam pilsētas teritorijā, tā esošo apakšstaciju izvietojuma koriģēšanai rekonstrukcijas gadījumā. Rezultātā pilsētas elektroapgādes shēmas attīstība notiek nevis haotiski, bet mērķtiecīgi.

Ar aprēķinu programmu EXCEL un grafisko programmu AUTOCAD var automatizēt transformatoru apakšstaciju izvietojuma procedūru pilsētas kartē.

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