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ON THE QUESTION OF OPTIMIZING THE QUALITY OF ENERGY IN CITY ELECTRIC NETWORK

As is well known, ensuring the energy quality indicators set by the State Technical Service of Ukraine in electrical networks is an extremely important task. The heterogeneity of load schedules of consumers of urban electric networks in combination with the variety of their operating modes, phase differences, non-linearity and high speed of parameter changes led to the fact that asymmetry, non-sinusoidal, voltage deviations and fluctuations in the networks became permanent factors that significantly reduce the quality of the networks and consumers connected to them. In addition, studies of the power factor in urban electrical networks indicate a low level of reactive power compensation in them. This is due to the high value of voltage and power losses in networks, the technical need and economic feasibility of compensation of reactive power in them. Research conducted at O. M. Beketov Kharkiv National University of Urban Economy, testify to the fact that the main strategic directions for improving the quality of energy in urban electric networks are voltage regulation, taking into account the comprehensive solution of the issues of improving the quality of energy and compensation of reactive power. At the same time, the technical solution to the problem is on the way of multi-level correction of quality indicators by using additional multifunctional devices, the most important place among which is occupied by devices made on the basis of thyristor-controlled voltage transformers. The paper presents the results of this study. It is also determined that in combination with the automation of the process of managing multifunctional devices, the use of multifunctional converters as a whole allows solving the issue of optimizing the operation modes of city power supply systems. The application of research results in general allows solving the issue of energy quality optimization in urban electrical networks.

Keywords: optimization, electrical energy, quality of electrical energy, urban electrical networks, voltage regulation, compensation of reactive power.

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ДО ПИТАННЯ ПРО ОПТИМІЗАЦІЮ ЯКОСТІ ЕНЕРГІЇ У МІСЬКИХ ЕЛЕКТРИЧНИХ МЕРЕЖАХ

Як відомо, забезпечення встановлених ДСТУ показників якості енергії в електричних мережах є надважливим завданням. Неоднорідність графіків навантаження споживачів міських електричних мереж у поєднанні з розмаїттям їх режимів роботи, пофазною відмінністю, нелінійністю та високою швидкістю зміни параметрів зумовили те, що несиметрія, несинусоїдність, відхилення та коливання напруги в мережах стали постійно діючими факторами, що істотно знижують якість роботи мереж та підключених до них споживачів. Крім того, дослідження коефіцієнта потужності у міських електричних мережах вказують на низький рівень компенсації реактивної потужності в них. Цим зумовлюється високе значення втрат напруги та потужності в мережах, технічна потреба та економічна доцільність компенсації реактивної потужності в них. Дослідження, проведені у ХНУМГ ім. О.М. Бекетова, свідчать про те, що основними стратегічними напрямками підвищення якості енергії у міських електричних мережах є регулювання напруги з урахуванням комплексного вирішення питань підвищення якості енергії та компенсації реактивної потужності. При цьому технічне вирішення проблеми знаходиться на шляху багаторівневої корекції показників якості шляхом застосування додаткових пристроїв багатофункціонального призначення, найважливіше місце серед яких займають пристрої, виконані на базі вольтододавальних трансформаторів з тиристорним керуванням. У роботі представлено результати цього дослідження. Також визначено, що у поєднанні з автоматизацією процесу управління багатофункціональними пристроями застосування багатофункціональних перетворювачів в цілому дозволяє вирішувати питання оптимізації режимів роботи систем електропостачання міст. Застосування результатів дослідження загалом дозволяє вирішувати питання оптимізації якості енергії у міських електричних мережах.

Ключові слова: оптимізація, електрична енергія, якість електричної енергії, міські електричні мережі, регулювання напруги, компенсація реактивної потужності.

Introduction. As is well known [1], ensuring the energy quality indicators set by the State Technical Service of Ukraine in electrical networks is an extremely important task. The heterogeneity of load schedules of consumers of urban electric networks in combination with the variety of their operating modes, phase differences, non-linearity and high speed of parameter changes led to the fact that asymmetry, non-sinusoidal, voltage deviations and fluctuations in the networks became permanent factors that significantly reduce the quality of the networks and consumers connected to them. In addition, studies of the power factor in urban electric networks [2] indicate a low level of reactive power compensation in them. This is due to the high value of voltage and power losses in networks, the technical need and economic feasibility of compensation of reactive power in them.

Purpose of the article. The purpose of the article is to develop the scientific foundations of complex optimization of voltage regimes in urban electrical networks.

Analysis of the state of the issue and purpose. Research conducted at O. M. Beketov Kharkiv National University of Urban Economy [3], testify to the fact that the main strategic directions of improving the quality of energy in urban electric networks are voltage regulation, taking into account the complex solution of the issues of improving the quality of energy and compensation of reactive power. At the same time, the technical solution to the problem is on the way of multi-level correction of quality indicators by using additional multifunctional devices, the most important place among which is occupied by devices made on the basis of thyristor-controlled voltage transformers [4–14].

Main part. The combination of the advantages of magnetic and semiconductor technology in these devices allows solving the issue of the main contactless regulation of the module and the phase of the additional EMF in a simple and convenient way. This solves the issues of voltage regulation and symmetrisation. In addition, the use of single-phase devices with uncoupled dose control systems makes it possible to additionally solve the issue of balancing currents, as well as reactive power compensation. At the same time, the sequential inclusion of the secondary (additional voltage) winding of the voltage-boosting transformer with a load causes the transmission of only an additional amount of electrical energy, proportional to the value of the additional EMF, through the transformer. This circumstance explains the small value of the installed capacity of the step-up transformers, their improved weight and size and cost indicators, as well as the low value of power and energy losses in them.

Fig. 1 shows the schematic diagram of the device made on the basis of three single-phase voltage-input phase-switching transformers, and Fig. 2 shows the vector voltage diagram. As can be seen from Fig. 2, the voltage at the output of each of the phases of the device is the geometric sum of the voltages of each of the phases and the EMF induced in the secondary windings of the transformers, the vectors of which rotate around point 0 when the connection schemes of the primary windings change. At the same time, depending on the connection scheme of the exciting winding for each of the phases, 12 positions of the secondary EMF vector E_2 can be obtained.

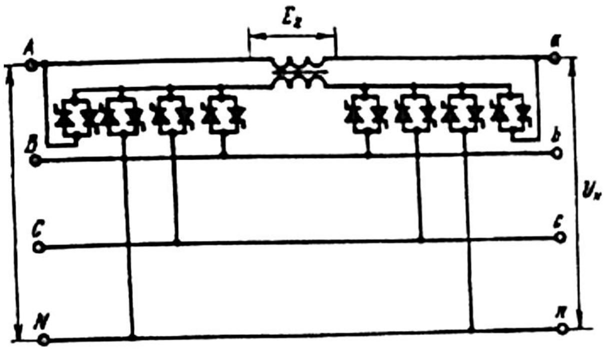

Figure 1 – Schematic diagram of the device made on the basis of three single-phase voltage-supplying phase-switching transformers

By analogy with conventional power transformers, when determining voltage additions created by the device, it is convenient to use the designations of winding connection groups. At the same time, odd groups can be obtained by connecting some of the windings in a star, others in a triangle. Even groups are formed by the same connection schemes of windings of the same name, i.e. star-star or triangle-triangle.

If the additional voltage windings are included in the star, then when the exciting windings are connected, six even ones (II, IV, VI, VIII, X, XII) are formed in the star, and when they are connected in a triangle, six odd ones (I, III, V, VII, IX, XI) groups of connection of windings. At the same time, in connection with the connection of the exciting windings to the linear voltage, the EMF E_2 induced in the secondary winding increases by 3 times.

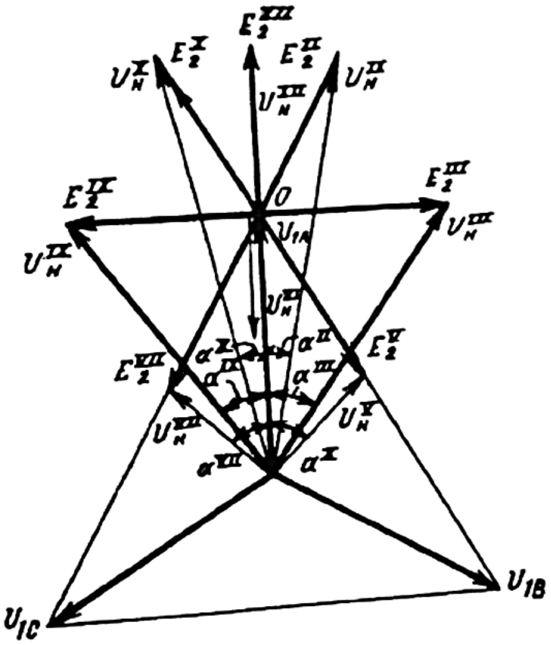

Figure 2 – Vector voltage diagram

The value of the output voltage for each of the positions of the vector of the secondary EMF E_2 can be obtained by solving the expressions drawn up for a triangle, one side of which is the network voltage vector, and the other is the EMF vector E_2 (the angle between them is a multiple of 30°):

- for paired groups:

$$U_н=U_2+E_2=\sqrt{E_2^2\sin^2\alpha+(U_1\text{-}E_2\sin\alpha)^2}=U_1\sqrt{\frac{1}{k_T^2}\sin^2\alpha+\left(U_1\text{-}\frac{U_1}{k_T}\sin\alpha\right)^2}==U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}\text{-}2\cos\alpha\right)+1}; \quad (1)$$

- for odd groups:

$$U_н=U_2+\sqrt{3}E_2=\sqrt{3E_2^2\sin^2\alpha+\left(U_1\text{-}E_2\sqrt{3}\cos\alpha\right)^2}=\sqrt{\frac{3U_1^2}{k_T^2}\sin^2\alpha+\left(U_1\text{-}\frac{\sqrt{3}U_1}{k_T}\cos\alpha\right)^2}==U_1\sqrt{\frac{1}{k_T}\left(\frac{3}{k_T}\text{-}2\sqrt{3}\cos\alpha\right)+1}, \quad (2)$$

here U_1 is the phase value of the network voltage;

k_T is the transformation factor of the voltage transformer;

α is the angle between the network voltage U_1 and EMF E_2, which depends on the connection group of the transformer windings.

The value of the phase shift $\varphi_н$ of the output voltage $U_н$ with respect to U_1 can be determined from the following expressions:

- for paired groups:

$$\varphi_{н}^{н}=\mathrm{arctg}\frac{1-\frac{1}{k_T}\cos\alpha}{\frac{1}{k_T}\sin\alpha};\qquad(3)$$

- for odd groups:

$$\varphi_{н}^{н}=\mathrm{arctg}\frac{1-\frac{\sqrt{3}}{k_T}\cos\alpha}{\frac{\sqrt{3}}{k_T}\sin\alpha}.\qquad(4)$$

Thus, the use of phase-switching voltage transformers allows obtaining 12 voltage additions different in value and sign and the same number of phase shifts. Moreover, a negative addition of voltage means a decrease in the value of the output voltage, and a negative value of the phase angle means an advance of the output voltage of the network. The calculated values of voltage additives and the corresponding phase angles for the considered 12 groups of connection of primary windings are given in Table 1.

Table 1 – Calculated values of voltage additives and corresponding phase angles for the considered 12 groups of connection of primary windings

Connection group	Output voltage	Phase shift of the output voltage
XII	$U_н=U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}+2\right)+1}$	$\varphi_н=0$
I or XI	$U_н=U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}+1{,}732\right)}$	$\varphi_н=\pm\,\mathrm{arctg}\frac{0{,}5}{k_T-0{,}866}$
II or X	$U_н=U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}+1\right)+1}$	$\varphi_н=\pm\,\mathrm{arctg}\frac{0{,}866}{k_T-0{,}5}$
III or IX	$U_н=U_1\sqrt{\frac{1}{k_T^2}+1}$	$\varphi_н=\pm\,\mathrm{arctg}\frac{1}{k_T}$
IV or VIII	$U_н=U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}+1{,}732\right)}$	$\varphi_н=\pm\,\mathrm{arctg}\frac{0{,}5}{k_T+0{,}866}$
V or VII	$U_н=U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}-1\right)+1}$	$\varphi_н=\pm\,\mathrm{arctg}\frac{0{,}866}{k_T+0{,}5}$
VI	$U_н=U_1\sqrt{\frac{1}{k_T}\left(\frac{1}{k_T}-2\right)+1}$	$\varphi_н=0$

The joint use of regulating and compensating devices in power supply systems allows:

- minimize the power of additional control devices;
- simplify management and regulation schemes;
- reduce losses of active power.

In combination with the automation of the process of managing multifunctional devices, the use of multifunctional converters as a whole allows solving the issue of optimizing the operation modes of city power supply systems.

An important feature of the use of the mentioned devices in urban electric networks is the multidimensionality and interconnection of indicators of the quality of electric energy, which fundamentally does not allow for autonomous control. The optimal solution in this case can be obtained in the form of a combination of quality indicators. Taking into account the numerical and physical incommensurability of indicators for these conditions, a criterion related to economic indicators, in particular, the minimum specified costs for the production, transmission and distribution of a given amount of electric energy, can be adopted as a criterion of optimality. In this case, quality indicators with different characteristics are comparable due to economic parameters characterizing probable material losses from low-quality electrical energy.

As for the considered problem, the integral quadratic functional of the following criterion functions can be used as a criterion for the optimality of energy quality at a given point in the network: voltage deviation δU, voltage change range δU_t, voltage non-sinusoidal coefficient $K_{нсU}$, zero sequence coefficient K_{0U}, power coefficient $\cos\varphi$. In general, we have:

$$Q=\int_0^T\sum_{i=1}^{n}\gamma_i\overline{\varphi}_i^2(t)\,dt\rightarrow\min,\qquad(5)$$

here γ_i – weight coefficient of the *i*-th function;

$\overline{\varphi}_i=\frac{(\varphi_i-\varphi_{iном})}{\varphi_{iном}}$ – criterion function of the *i*-th indicator;

T – observation time;

n – number of indicators;

$\varphi_{iном}$ is the nominal value of the *i*-th indicator function.

In the formulation under consideration, the task of optimal control is reduced to the minimization of the functional (5) when the system moves from position φ_0 to position φ_T. In general, the considered problem belongs to the variation class and is solved by multi-criteria optimization methods. Given the non-antagonism of the contradictions between the functions $\varphi_i(t)$, the conditions for joint achievement of various goals can be determined using the method of weighting coefficients.

Due to the low reliability of the information needed for decision-making, the determination of the weighting factors characterizing the influence of the *i*-th indicator on the efficiency of the power supply system was carried out using the method of expert evaluations [5]. Specialists of electric network enterprises, which have city electric networks on their balance sheets, were used as experts. The ranking of energy quality indicators by the degree of their influence on the efficiency of the power supply system was carried out according to a 10-point system, each of the energy quality indicators was considered as a numerical variable x, which can take on random values: $x_1, x_к, \ldots, x_r$. The generalized group assessment of experts is defined in the form of a mathematical expectation:

$$M_i=\frac{1}{m}\sum_{j=1}^{m}C_{ij},\qquad(6)$$

here i – indicator number;

j – number of the expert;

m – the number of experts who gave an assessment;

C_{ij} – evaluation of the *i*-th indicator by the *i*-th expert.

To assess the homogeneity of the opinion of the group of experts, the variance D_i and the root mean square deviation σ_i were calculated for each *i*-th display:

$$D_i=\frac{1}{m-1}\sum_{j=1}^{m}\left(C_{ij}-M_i\right)^2, \qquad (7)$$

$$\sigma_i=\sqrt{D_i} \qquad (8)$$

The degree of consistency of experts' opinion is estimated by the coefficient of variation:

$$V_i=\frac{\sigma_i}{M_i}\cdot 100\%. \qquad (9)$$

The values of the weighting coefficients in (5) are taken as equal:

$$\gamma=\frac{M_i}{M_{max}}. \qquad (10)$$

here M_{max} is the evaluation value for the most significant indicator.

The results of calculations are given in Table. 2.

Table 2 – Results of the calculation of the weighting coefficients of the quality indicators

Name of indicators	Voltage deviation, δU	Voltage change amplitude, δU_1	Zero sequence coefficient, K_{0U}	Non-sinusoidal coefficient, $K_{нсU}$	Power factor, cosφ
Mathematical score expectation, M_i	7.6	2.4	5,6	0.8	3.6
Coefficient of variation, V_i%	3.6	16.7	7.2	55.0	11.1
Weighting factor, γ_i o.e.	0.38	0.12	0.27	0.04	0.19

Conclusions. The coincidence of many characteristics indicates the correct choice of “generalizing” assessment. The greatest significance of the mathematical expectation of points is the voltage deviation δU (7.6 points), the zero-sequence coefficients K_{0U} (5.6 points) and the power cosφ (3.6 points), which, according to experts, indicates a high degree of their influence on the technical - economic indicators of power supply systems. It’s slightly lower value for the range of voltage changes δU_t (2.4 points) is explained by the lower impact of voltage fluctuations on the technical and economic indicators of the city's power supply systems. The small value of the mathematical expectation of points for the non-sinusoidal coefficient of the current and voltage curves indicates the insignificant influence of this indicator on the technical and economic indicators of the power supply systems of cities at the current stage of their development. The slightly increased value of the coefficients of variation V_i for the non-sinusoidal weighting factor is explained by the ambiguity of its assessment by experts of different energy systems, caused by the difference in the composition of consumers and the level of their electromagnetic compatibility. Moreover, its greatest importance concerns the power supply systems of industrialized cities (Mariupol, Zaporizhzhia, Dnipro, Kharkiv, etc.). The low value of the coefficients of variation V and the weighting factor of voltage deviations is due to the unity of opinions of experts regarding the assessment of the degree of influence of voltage deviations on the technical and economic indicators of networks and consumers connected to them. In general, the calculated values of the coefficients of variation of various weighting factors indicate a fairly high consistency of experts' opinions and the possibility of practical application of the obtained results. The use of tabular data in combination with (5) allows solving the issue of optimizing the quality of energy in urban electrical networks. In this case, the optimality criterion will be $Q = Q_{min}$.

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