Вирішено актуальну наукову задачу мінімізації збитків, спричинених усталеним відхиленням та несиметрією напруг в розподільних електричних мережах номінальною напругою 10 кВ.

Встановлено, що існуючі системи автоматичного керування параметрами режиму розподільних електричних мереж не в повній мірі враховують багатофункціональний вплив симетро-компенсуючих пристроїв на рівні показників якості електроенергії.

Запропоновано в якості критеріальних функцій задачі автоматичного керування рівнем показників якості електроенергії використовувати функціональні залежності, що оцінюють рівень збитків, спричинених усталеним відхиленням та несиметрією напруг в електричних мережах. Це дозволило, на відміну від існуючих систем керування, в більш повній мірі врахувати негативний вплив від усталеного відхилення та несиметрії напруг на режими роботи електричної мережі.

Визначено функціональні залежності між вхідними та вихідними параметрами об'єкта керування (розподільної електричної мережі напругою 10 кВ з симетро-компенсуючим пристроєм), які лягли в основу критеріальних функцій задачі багатокритеріальної оптимізації. Знаходження кінцевого розв'язку задачі багатокритеріальної оптимізації методом наближення до утопічної точки в просторі критеріїв здійснювалось шляхом мінімізації чебишевської відстані від утопічної точки до парето-оптимальної множини розв'язків. На основі знайденого розв'язку задачі багатокритеріальної оптимізації розроблено алгоритм визначення вектора оптимального керування.

Проведено комп'ютерне імітаційне моделювання оптимальної системи автоматичного керування рівнем показників якості електроенергії в розподільних електричних мережах.

Аналіз результатів моделювання показав, що запропонована в роботі система автоматичного керування, в порівнянні з існуючими, дозволяє знизити негативний вплив понаднормових значень усталеного відхилення та несиметрії напруг на роботу електричних мереж

Ключові слова: система автоматичного керування, показники якості електроенергії, багатокритеріальна оптимізація, несиметрія напруги

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IMPROVING THE OPTIMAL SYSTEM OF AUTOMATED CONTROL OVER THE LEVEL OF ELECTRIC POWER QUALITY INDICATORS IN ELECTRIC NETWORKS

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1. Introduction

The current stage of the global power generation development is characterized by a significant aggravation of the issue related to the operational efficiency of distributing electrical networks (DENs). One of the main reasons for the compromised efficiency and the less cost-effective operation of DENs is the deterioration of electricity quality. This problem is especially acute for the distributing networks with a rated voltage of 10 kV, which power large asymmetric electricity consumers (induction furnaces, arc steel furnaces, etc.). Such DENs are typically characterized by excessive inflated values of the established voltage deviation and a coefficient of voltage asymmetry in reverse sequence, which negatively influences the operation of electric receivers [1].

The most effective way to reduce the levels of the specified electricity quality indicators (EQIs) is the use of specialized technical means – symmetry-compensating devices (SCDs). These devices exert a multifunctional influence on the DEN mode settings, which imposes certain requirements for the automated control systems (ACS) of the SCD operation mode.

Our analysis of existing ACSs of the SCD operation mode has revealed that most such systems do not fully take into consideration the multifunctional influence of the SCD settings on the DEN mode parameters, which can cause an increase in the levels of PEQI, which characterize the established deviation and the asymmetry of voltage. This, in turn, leads to an increase in the negative impact of the above-the-norm values of the established voltage deviation and the voltage asymmetry coefficient in the reverse sequence on the operation of DEN.

Given this, it is a relevant task to improve the ACS of the DEN operation with SCD in order to minimize the negative impact exerted on the DEN operation by the established deviation and the asymmetry of voltage.

2. Literature review and problem statement

Paper [2] proposed an ACS for the mode parameters of distributing electrical networks, the application of which makes it possible to achieve a simultaneous reduction in the established voltage deviation and a decrease in the reactive power consumption from the electric network. The disadvantage of the approach described in [2] to automated control is the need to apply a three-phase controlled voltage source, which significantly increases investment in a distributing electrical network. In addition, the specified automated control system does not influence the level of the asymmetry of voltages in an electrical network.

Work [3] proposed, in order to simultaneously reduce the levels of voltage asymmetry and a coefficient of reactive power, to use specialized technical means – active symmetry-compensating devices (an analog to a three-phase active filter). The cited work showed that the reactive and asymmetrical components of current could be fully compensated for in such a device, even in the case of a distorted sinusoidality in the shape of the current and voltage curves. A similar approach to lowering the EQI levels in distributing electric networks is proposed in study [4]. The cited study reported an algorithm of ACS operation for a unified electric energy quality stabilizer (UPQC) based on the power angle control (PAC) using the synchronous reference system (SRF). The ACS described in [4] helps improve the harmonic profile of voltage and current, and reduces the levels of the established deviation and the asymmetry of voltages. Work [5] suggested, for a simultaneous decrease in the EQI levels and a reactive power factor, using the static compensators (SVC) with an adaptive ACS, which ensures high efficiency of their work under conditions of dramatically-changing asymmetrical loading. A similar approach is described in [6], which proposes an algorithm for automated control over the static synchronous compensator (DSTATCOM), based on determining the level of asymmetry of voltages caused by electric loads (by electricity consumer). The implementation of such an algorithm can significantly reduce the power of a static synchronous compensator. The most significant common disadvantage of approaches to lowering the EQI levels described in [3–6] is the need to use costly powerful semiconductor devices.

An optimal ACS for symmetry-compensating devices was proposed in paper [7], which makes it possible to achieve a simultaneous reduction in the levels of the established voltage deviation, asymmetry of voltages, and a reactive power coefficient. A special feature of this ACS is a centralized approach to the automated control over the mode parameters of the entire distributing electric network rather than a separate load connection point. The effectiveness of the ACS proposed in [7] was confirmed by simulation results obtained by using the modified testing systems IEEE 34 and IEEE 123. The main drawback of the ACS proposed in paper [7] is its limited scope of application only in electrical networks with a rated voltage to 1 kV.

Studies [8, 9] suggested the ACSs of the operation mode of the symmetry-compensating devices in DENs with rated voltage of 0.4 kV [8] and 10 kV [10]. The ACSs designed in the cited studies are based on the solutions to a problem on multi-criteria optimization. The application of the specified ACSs makes it possible to achieve a simultaneous reduction in the levels of the established voltage deviation, the asymmetry of voltages, and a coefficient of DEN reactive power. However, the main drawback of these ACSs is that they do not fully take into consideration the capability of the symmetry-compensating devices to reduce the level of negative impact caused by the established deviation and the asymmetry of voltage. Given this, there is a need for further research into a given issue.

3. The aim and objectives of the study

The aim of this study is to improve the optimal system of automated control over the levels of established deviation and a voltage asymmetry coefficient in the reverse sequence in electrical networks. This would make it possible to reduce the negative impact exerted by the above-the-norm values of the specified electricity quality indicators on the operation of distributing electrical networks with a voltage of 10 kV.

To accomplish the aim, the following tasks have been set:

– to define the criteria functions for a multi-criteria optimization problem, which take into consideration the negative impact of the established deviation and the asymmetry of voltage on the operation of distributing power grids with a voltage of 10 kV and to choose a method to solve a given problem;

– to develop a computer simulation model of an ACS over the level of electricity quality indicators in the distributing electrical networks with a voltage of 10 kV and to determine the possible effect from the use of the developed ACS by using it.

4. Studying the system of automated control over the electricity quality indicators in a distributing electrical network

4. 1. Stating and solving the problem of multi-criteria optimization of QEI levels in a distributing electrical network

One of the ways to improve the efficiency of DEN operation, namely, to reduce the negative impact of the QEI inflated levels that characterize the established deviation and the asymmetry of voltage, is to improve an ACS over the SCD operation regime.

As shown in [9], the task on a simultaneous decrease in the established deviation and the asymmetry of voltages, as well as on a reduction in the reactive power consumption from the power system, should be considered as a multi-criteria optimization problem. For the case of a network with the isolated neutral, such a control problem is stated in the following form [9]:

$$\begin{cases} \mathrm{tg}\varphi(\mathbf{X}) = \dfrac{Q_s(\mathbf{X})}{P_s(\mathbf{X})} \to \min; \\ \Delta U_1(\mathbf{X}) = \left| \dfrac{U_1(\mathbf{X}) - U_{nom}}{U_{nom}} \right| \cdot 100 \to \min; \\ k_{2U}(\mathbf{X}) = \dfrac{U_2(\mathbf{X})}{U_{nom}} \cdot 100 \to \min; \\ \mathbf{X} \in \Omega, \end{cases} \tag{1}$$

where $\mathbf{X}=[X_{AB}, X_{BC}, X_{CA}]$ is the vector of reactive resistances of the SCD phases (control vector); $\mathrm{tg}\varphi(\mathbf{X})$ is the coefficient of reactive power; $P_s(\mathbf{X})$, $Q_s(\mathbf{X})$ is, respectively, the active and reactive power consumed from the grid; $U_1(\mathbf{X})$ is the module of the current value of a direct sequence voltage; $\Delta U_1(\mathbf{X})$ is the established deviation of a three-phase voltage of the network; U_{nom} is the rated linear voltage of the network; $k_{2U}(\mathbf{X})$ is the reverse sequence voltages; $U_2(\mathbf{X})$ is the module of the current value of a reverse sequence voltage; $\Omega = \mathbb{R}^3 \,|\, X_{i\min} \le X_i \le X_{i\max}$, $i = AB,\ BC,\ CA$ is the region of permissible **X** values, defined by the range of SCD adjustment (permissible control space); $X_{i\min}$, $X_{i\max}$ are, respectively, the minimum and maximum value of SCD resistances for each phase.

The criteria functions for the multicriteria optimization problem (1) include the functional dependences of EQI levels (the established voltage deviation ΔU_1 and a voltage asymmetry coefficient in the reverse sequence k_{2U}) on the control vector **X**. However, it is known that the negative impact exerted on DEN operation by the above-the-norm values ΔU_1 and k_{2U} is not equal and can differ considerably depending on the qualitative and quantitative composition of an electric load. Therefore, a more promising approach appears to be one at which the criteria functions for problem (1) are the dependences assessing the negative impact of the deviation and asymmetry of voltage on DEN operation. The problem on a multi-criteria optimization, which implements this approach, is stated in the following form:

$$\begin{cases} \mathrm{tg}\varphi(\mathbf{X}) = \dfrac{Q_s(\mathbf{X})}{P_s(\mathbf{X})} \to \min; \\ L_{\Delta U}(\mathbf{X}) = a_1\left[\Delta U_1(\mathbf{X}) + a_2\right]^2 \dfrac{S_l}{S_{l\max}} \to \min; \\ L_{k2U}(\mathbf{X}) = c_0 \sum\limits_{j=1}^{m} k_j k_{2U}^2(\mathbf{X}) \to \min; \\ X \in \Omega, \end{cases} \tag{2}$$

where $L_{\Delta U}$ is the indicator that evaluates the negative impact caused by the established voltage deviation ΔU_1; a_1, a_2 are the constant coefficients, which depend on the qualitative composition of an electric load; S_l is the current value of full power of an electric load; $S_{l\max}$ is the maximum value of full power of an electric load; L_{k2U} is the indicator that evaluates the negative impact caused by the asymmetry of voltage; c_0 is the effective tariff for electrical energy; k_j is the coefficient of additional losses of active power due to the asymmetry of voltages for the j-th group of homogeneous power supply system elements; m is the number of groups of homogeneous power supply systems.

To find the solutions to a multicriteria optimization problem (2), it is necessary, first, to define the interrelations between the input and output parameters of a control object (a DEN with SCD).

Fig. 1 shows the replacement circuit of an electric network with a rated voltage of 10 kV, which includes SCD.

In Fig. 1: $\underline{E}_A$, $\underline{E}_B$, $\underline{E}_C$ – emf complexes of the power system in phases *A, B, C*, respectively; R_{sA}, X_{sA}, R_{sB}, X_{sB}, R_{sC}, X_{sC} – equivalent active and inductive resistances of phases *A, B, C* of the power system (respectively, complex resistances of the system – $\underline{Z}_{sA} = R_{sA} + jX_{sA}$, $\underline{Z}_{sB} = R_{sB} + jX_{sB}$, $\underline{Z}_{sC} = R_{sC} + jX_{sC}$); R_{lAB}, X_{lAB}, R_{lBC}, X_{lBC}, R_{lCA}, X_{lCA} – active and inductive resistances of phases *AB*, *BC*, *CA* of equivalent load, connected by the scheme «triangle» (respectively, complex load resistances – $\underline{Z}_{lAB} = R_{sAB} + jX_{sAB}$, $\underline{Z}_{lBC} = R_{sBC} + jX_{sBC}$, $\underline{Z}_{lCA} = R_{sCA} + jX_{sCA}$); X_{AB}, X_{BC}, X_{CA} – capacitive resistances of phases *AB*, *BC*, *CA* if SCD, connected by the scheme «triangle»; $\underline{I}_{sA}$, $\underline{I}_{sB}$, $\underline{I}_{sC}$ – phase currents in phases *A, B, C* of the power system; $\underline{I}_{lA}$, $\underline{I}_{lB}$, $\underline{I}_{lC}$ – linear currents in phases *A, B, C* of the load; $\underline{I}_{lAB}$, $\underline{I}_{lBC}$, $\underline{I}_{lCA}$ – phase currents in phases *AB*, *BC*, *CA* of the equivalent load, connected according to the «triangle» scheme; $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$ – linear currents in phases *A, B, C* of SCD; $\underline{I}_{AB}$, $\underline{I}_{BC}$, $\underline{I}_{CA}$ – phase currents in phases *AB*, *BC*, *CA* of SCD; $\underline{U}_{AB}$, $\underline{U}_{BC}$, $\underline{U}_{CA}$ – linear voltages between phases *AB*, *BC*, *CA* at a point where SCD and load are connected.

To determine the relationship between the input and output signals in a control object, it is advisable to apply the approach similar to that described in work [8], which implies dividing the problem into 2 stages.

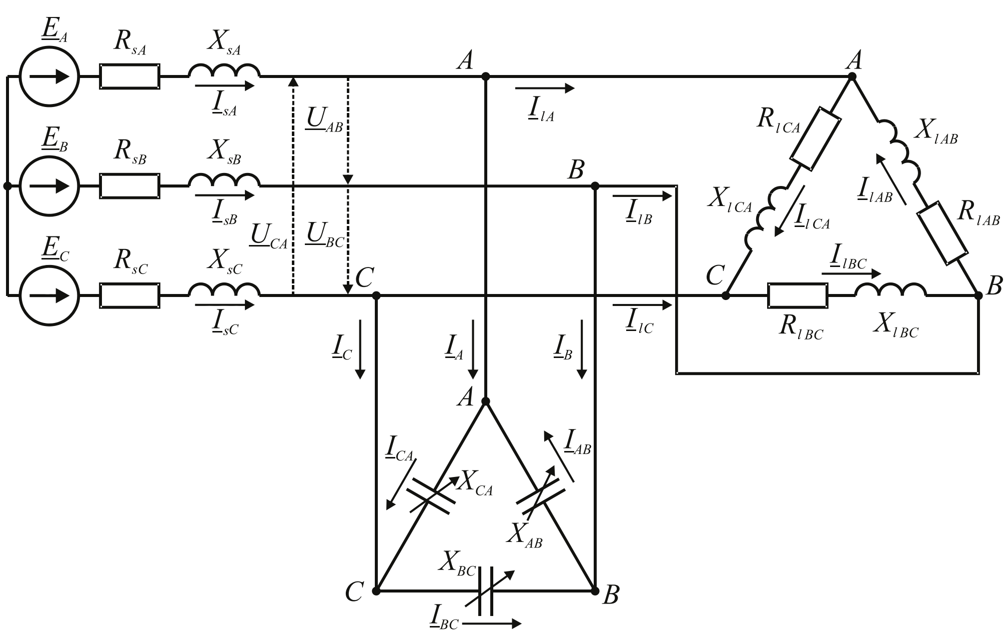


Fig. 1. The replacement circuit of an electric network with a rated voltage of 10 kV, which includes SCD

Stage 1. Based on the known measured values of the output magnitudes of the control object (linear load currents $\underline{I}_{lA}$, $\underline{I}_{lB}$, $\underline{I}_{lC}$, interphase voltages $\underline{U}_{AB}$, $\underline{U}_{BC}$, $\underline{U}_{CA}$, phase voltages $\underline{U}_A$, $\underline{U}_B$, $\underline{U}_C$), parameters of the model (the phase resistances of the power system $\underline{Z}_{sA}$, $\underline{Z}_{sB}$, $\underline{Z}_{sC}$), and the values of control influences (capacitive resistances of SCD X_{AB}, X_{BC}, X_{CA}), we determine the values for the magnitudes of perturbations not subjected to direct measurements ($\underline{Z}_{lAB}$, $\underline{Z}_{lBC}$, $\underline{Z}_{lCA}$, $\underline{E}_A$, $\underline{E}_B$, $\underline{E}_C$).

Stage 2. When one has complete information about the mathematical model of the control object, one determines the relationship between the controlling influences (X_{AB}, X_{BC}, X_{CA}) and output magnitudes ($\underline{I}_{lA}$, $\underline{I}_{lB}$, $\underline{I}_{lC}$, $\underline{U}_{AB}$, $\underline{U}_{BC}$, $\underline{U}_{CA}$, $\underline{U}_A$, $\underline{U}_B$, $\underline{U}_C$).

Determining the resistances of load $\underline{Z}_{lAB}$, $\underline{Z}_{lBC}$, $\underline{Z}_{lCA}$ is best performed as follows. First of all, we equivalently convert the load resistances $\underline{Z}_{lAB}$, $\underline{Z}_{lBC}$, $\underline{Z}_{lCA}$ for the replacement circuit in Fig. 1, from the scheme of «triangle» in the equivalent scheme of «star» based on known formulae:

$$\begin{cases} \underline{Z}_{lA} = \dfrac{\underline{Z}_{lAB}\underline{Z}_{lBC}}{\underline{Z}_{lAB}+\underline{Z}_{lAB}+\underline{Z}_{lCA}}; \\ \underline{Z}_{lB} = \dfrac{\underline{Z}_{lBC}\underline{Z}_{lAB}}{\underline{Z}_{lAB}+\underline{Z}_{lAB}+\underline{Z}_{lCA}}; \\ \underline{Z}_{lC} = \dfrac{\underline{Z}_{lCA}\underline{Z}_{lBC}}{\underline{Z}_{lAB}+\underline{Z}_{lAB}+\underline{Z}_{lCA}}, \end{cases} \tag{3}$$

where $\underline{Z}_{lA}$, $\underline{Z}_{lB}$, $\underline{Z}_{lC}$ are the complexes of resistances of phases *A, B, C* of the equivalent load connected according to the «stars» scheme.

Determining the resistances $\underline{Z}_{lA}$, $\underline{Z}_{lB}$, $\underline{Z}_{lC}$ is carried out according to the Ohm's law:

$$\begin{cases} \underline{Z}_{lA} = R_{lA} + jX_{l} = \dfrac{\underline{U}_A}{\underline{I}_{lA}}; \\ \underline{Z}_{lB} = R_{lB} + jX_{lB} = \dfrac{\underline{U}_B}{\underline{I}_{lB}}; \\ \underline{Z}_{lC} = R_{lC} + jX_{lC} = \dfrac{\underline{U}_C}{\underline{I}_{lC}}. \end{cases} \tag{4}$$

By using, for the load resistances, the reverse conversion of the circuit from the «star» to the equivalent «triangle», we obtain the desired resistances $\underline{Z}_{lAB}$, $\underline{Z}_{lBC}$, $\underline{Z}_{lCA}$:

$$\begin{cases} \underline{Z}_{lAB} = \underline{Z}_{lA} + \underline{Z}_{lB} + \dfrac{\underline{Z}_{lA}\underline{Z}_{lB}}{\underline{Z}_{lC}}; \\ \underline{Z}_{lBC} = \underline{Z}_{lB} + \underline{Z}_{lC} + \dfrac{\underline{Z}_{lB}\underline{Z}_{lC}}{\underline{Z}_{lA}}; \\ \underline{Z}_{lCA} = \underline{Z}_{lC} + \underline{Z}_{lA} + \dfrac{\underline{Z}_{lC}\underline{Z}_{lA}}{\underline{Z}_{lB}}. \end{cases} \tag{5}$$

To determine the emf of $\underline{E}_A$, $\underline{E}_B$, $\underline{E}_C$, it is necessary, first, to find currents of the power system $\underline{I}_{sA}$, $\underline{I}_{sB}$, $\underline{I}_{sC}$. For this purpose, it is necessary to use the expressions according to the first law by Kirchhoff, recorded for nodes *A, B, C* of the circuit shown in Fig. 1:

$$\begin{cases} \underline{I}_{sA} = \underline{I}_A + \underline{I}_{lA}; \\ \underline{I}_{sB} = \underline{I}_B + \underline{I}_{lB}; \\ \underline{I}_{sC} = \underline{I}_C + \underline{I}_{lC}. \end{cases} \tag{6}$$

The expressions for finding the values of SCD currents $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$, according to the Ohm's law, are as follows:

$$\begin{cases} \underline{I}_A = \dfrac{\underline{U}_{AB}}{-jX'_{AB}} - \dfrac{\underline{U}_{CA}}{-jX'_{CA}}; \\ \underline{I} = \dfrac{\underline{U}_{BC}}{-jX'_{BC}} - \dfrac{\underline{U}_{AB}}{-jX'_{AB}}; \\ \underline{I}_C = \dfrac{\underline{U}_{CA}}{-jX'_{CA}} - \dfrac{\underline{U}_{BC}}{-jX'_{BC}}, \end{cases} \tag{7}$$

where X'_{AB}, X'_{BC}, X'_{CA} are the values of SCD reactive resistances in phases *AB*, *BC*, *CA* at the previous step of control (before executing a controlling influence).

Fig. 1 shows that the load resistances and the SCD capacitive resistances are connected in parallel. Given this, the expressions for finding the equivalent resistance of SCD and the load take the following form:

$$\begin{cases} \underline{Z}'_{AB} = \dfrac{jX'_{AB}\underline{Z}_{lAB}}{jX'_{AB} - \underline{Z}_{lAB}}; \\ \underline{Z}'_{BC} = \dfrac{jX'_{BC}\underline{Z}_{lBC}}{jX'_{BC} - \underline{Z}_{lBC}}; \\ \underline{Z}'_{CA} = \dfrac{jX'_{CA}\underline{Z}_{lCA}}{jX'_{CA} - \underline{Z}_{lCA}}. \end{cases} \tag{8}$$

It is necessary, for the further simplification of the circuit, to convert the «triangle» of resistances $\underline{Z}'_{AB}$, $\underline{Z}'_{BC}$, $\underline{Z}'_{CA}$ to the equivalent «star» according to the expressions similar to (3). The result will be the equivalent complex resistances $\underline{Z}'_A$, $\underline{Z}'_B$, $\underline{Z}'_C$.

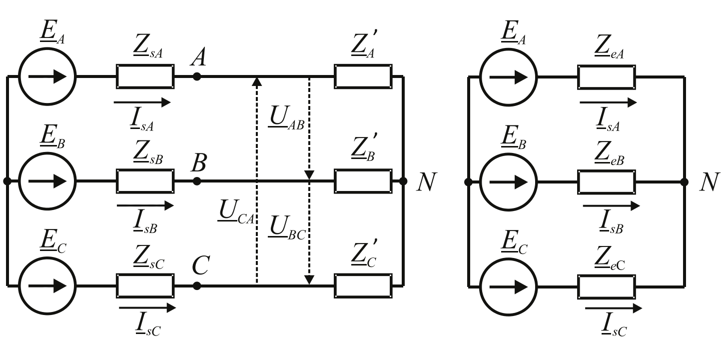
The expressions for finding equivalent phase $\underline{Z}_{eA}$, $\underline{Z}_{eB}$, $\underline{Z}_{eC}$ resistances of the replacement circuit take the following form:

$$\begin{cases} \underline{Z}_{eA} = \underline{Z}_{sA} + \underline{Z}'_A; \\ \underline{Z}_{eB} = \underline{Z}_{sB} + \underline{Z}'_B; \\ \underline{Z}_{eC} = \underline{Z}_{sC} + \underline{Z}'_C. \end{cases} \tag{9}$$

The general view of the replacement circuit after the transforms based on formulae (8), (9) is shown in Fig. 2.

Typically, a change in the loads in a DEN with a rated voltage of 10 kV almost does not affect the operation modes of synchronous generators at power plants, in particular, such a change does not violate the symmetry of the system emf. Therefore, in determining the emf of the system $\underline{E}_A$, $\underline{E}_B$, $\underline{E}_C$, one can assume that these emf form a symmetrical star. Given this assumption, it is possible, for the circuit in Fig. 2, *b*, to record, under the second law by Kirchhoff:

$$\begin{cases} \underline{I}_{sA}\underline{Z}_{eA} - \underline{I}_{sB}\underline{Z}_{eB} = \underline{E}_A - \underline{E}_B; \\ \underline{I}_{sB}\underline{Z}_{eB} - \underline{I}_{sC}\underline{Z}_{eC} = \underline{E}_B - \underline{E}_C; \\ \underline{E}_A + \underline{E}_B + \underline{E}_C = 0. \end{cases} \tag{10}$$



a *b*

Fig. 2. A replacement circuit for DEN after equivalent transforms: *a* – simplified replacement circuit; *b* – equivalent replacement circuit

Solving the system of equations (10) relative to $\underline{E}_A$, $\underline{E}_B$, $\underline{E}_C$, we obtain the expressions for finding the system emf:

$$\begin{cases} \underline{E}_A = \dfrac{2\underline{I}_{sA}\underline{Z}_{eA} - \underline{I}_{sB}\underline{Z}_{eB} - \underline{I}_{sC}\underline{Z}_{eC}}{3}; \\ \underline{E}_B = \dfrac{2\underline{I}_{sB}\underline{Z}_{eB} - \underline{I}_{sA}\underline{Z}_{eA} - \underline{I}_{sC}\underline{Z}_{eC}}{3}; \\ \underline{E}_C = \dfrac{2\underline{I}_{sC}\underline{Z}_{eC} - \underline{I}_{sB}\underline{Z}_{eB} - \underline{I}_{sA}\underline{Z}_{eA}}{3}. \end{cases} \quad (11)$$

Thus, by using formulae (3) to (5) and (11), it is possible to determine the magnitudes of perturbations that cannot be measured directly – the resistances of the load and the system emf, which is the solution to the first stage of the problem of defining the interrelations between the input and output parameters of the control object.

As noted above, the second stage in solving the problem on finding the interrelations between the input and output parameters of the control object implies establishing the dependence of the values of currents $\underline{I}_{sA}$, $\underline{I}_{sB}$, $\underline{I}_{sC}$ and voltages $\underline{U}_{AB}$, $\underline{U}_{BC}$, $\underline{U}_{CA}$ on controlling influences X_{AB}, X_{BC}, X_{CA}. The procedure for establishing this dependence is as follows.

First, it is necessary, for the replacement circuit shown in Fig. 1, to perform the equivalent transformations according to formulae (3), (8), (9). The result will be a circuit shown in Fig. 2, *b*. It is obvious that the equivalent resistances $\underline{Z}_{eA}$, $\underline{Z}_{eB}$, $\underline{Z}_{eC}$ for the circuit shown in Fig. 2, *b* are functionally dependent on SCD resistances X_{AB}, X_{BC}, X_{CA} (to simplify the notation, further calculations will not include this dependence in an explicit form).

For the circuit in Fig. 2, *b*, it is necessary to solve the inverse problem: to determine, based on the known system emf $\underline{E}_A$, $\underline{E}_B$, $\underline{E}_C$ and equivalent resistances $\underline{Z}_{eA}$, $\underline{Z}_{eB}$, $\underline{Z}_{eC}$, the currents $\underline{I}_{sA}$, $\underline{I}_{sB}$, $\underline{I}_{sC}$. To this end, one needs to build a system of equations according to the first and second laws by Kirchhoff:

$$\begin{cases} \underline{I}_{sA}\underline{Z}_{eA} - \underline{I}_{sB}\underline{Z}_{eB} = \underline{E}_A - \underline{E}_B; \\ \underline{I}_{sB}\underline{Z}_{eB} - \underline{I}_{sC}\underline{Z}_{eC} = \underline{E}_B - \underline{E}_C; \\ \underline{I}_{sA} + \underline{I}_{sB} + \underline{I}_{sC} = 0. \end{cases} \quad (12)$$

Solving the system of equations (12) relative to currents $\underline{I}_{sA}$, $\underline{I}_{sB}$, $\underline{I}_{sC}$ yields the following expressions:

$$\begin{cases} \underline{I}_{sA} = \dfrac{\underline{E}_A(\underline{Z}_{eB} + \underline{Z}_{eC}) - \underline{E}_B\underline{Z}_{eC} - \underline{E}_C\underline{Z}_{eB}}{\underline{Z}_{eA}\underline{Z}_{eB} + \underline{Z}_{eA}\underline{Z}_{eC} + \underline{Z}_{eB}\underline{Z}_{eC}}; \\ \underline{I}_{sB} = \dfrac{\underline{E}_B(\underline{Z}_{eA} + \underline{Z}_{eC}) - \underline{E}_A\underline{Z}_{eC} - \underline{E}_C\underline{Z}_{eA}}{\underline{Z}_{eA}\underline{Z}_{eB} + \underline{Z}_{eA}\underline{Z}_{eC} + \underline{Z}_{eB}\underline{Z}_{eC}}; \\ \underline{I}_{sC} = \dfrac{\underline{E}_C(\underline{Z}_{eA} + \underline{Z}_{eB}) - \underline{E}_A\underline{Z}_{eB} - \underline{E}_B\underline{Z}_{eA}}{\underline{Z}_{eA}\underline{Z}_{eB} + \underline{Z}_{eA}\underline{Z}_{eC} + \underline{Z}_{eB}\underline{Z}_{eC}}. \end{cases} \quad (13)$$

By using the expressions according to the second law by Kirchhoff and the ratios between the phase and linear voltages, we obtain the expressions to find the values of linear voltages $\underline{U}_{AB}$, $\underline{U}_{BC}$, $\underline{U}_{CA}$:

$$\begin{cases} \underline{U}_{AB} = \underline{U}_A - \underline{U}_B = \underline{I}_{sA}\underline{Z}'_A - \underline{I}_{sB}\underline{Z}'_B; \\ \underline{U}_{BC} = \underline{U}_B - \underline{U}_C = \underline{I}_{sB}\underline{Z}'_B - \underline{I}_{sC}\underline{Z}'_C; \\ \underline{U}_{CA} = \underline{U}_C - \underline{U}_A = \underline{I}_{sC}\underline{Z}'_C - \underline{I}_{sA}\underline{Z}'_A. \end{cases} \quad (14)$$

Thus, the interrelation between the input and output parameters of the control object (a DEN with SCD) is described by equations (13) and (14).

The module of the current value of a direct sequence voltage is determined from the following expression according to the method of symmetric components:

$$U_1(\mathbf{X}) = \left| \frac{1}{3}\begin{pmatrix} \underline{U}_{AB}(\mathbf{X}) + \\ +a\underline{U}_{BC}(\mathbf{X}) + a^2\underline{U}_{CA}(\mathbf{X}) \end{pmatrix} \right|, \quad (15)$$

where $a = e^{j2\pi/3}$ is a turning operator.

Similarly, the module of the current value of a reverse sequence voltage is determined from the following expression according to the method of symmetric components:

$$U_2(\mathbf{X}) = \left| \frac{1}{3}\begin{pmatrix} \underline{U}_{AB}(\mathbf{X}) + \\ +a^2\underline{U}_{BC}(\mathbf{X}) + a\underline{U}_{CA}(\mathbf{X}) \end{pmatrix} \right|. \quad (16)$$

To determine the linear voltages in expressions (15) and (16), one should use formulae (14).

It is advisable to find the expressions describing the interconnection between the control vector **X** and the values of the active and reactive powers consumed from the power system, by determining the full power. To this end, one must use the previously found expressions to determine the currents of the system (13) and the phase voltages (14).

The full power of phases *A*, *B*, *C*, consumed from the power system, is determined from formulae:

$$\begin{cases} \underline{S}_{sA}(\mathbf{X}) = \underline{U}_A(\mathbf{X})\hat{\underline{I}}_{sA}(\mathbf{X}); \\ \underline{S}_{sB}(\mathbf{X}) = \underline{U}_B(\mathbf{X})\hat{\underline{I}}_{sB}(\mathbf{X}); \\ \underline{S}_{sC}(\mathbf{X}) = \underline{U}_C(\mathbf{X})\hat{\underline{I}}_{sC}(\mathbf{X}); \\ \underline{S}_s(\mathbf{X}) = \underline{S}_{sA}(\mathbf{X}) + \underline{S}_{sB}(\mathbf{X}) + \underline{S}_{sC}(\mathbf{X}). \end{cases} \quad (17)$$

Given the expressions that are included in the system of equations (17), one can determine the active $P_s(\mathbf{X})$ and reactive $Q_s(\mathbf{X})$ powers consumed from the system by a three-phase load taking into consideration the generation of the reactive power from SCD:

$$\begin{cases} P_s(\mathbf{X}) = \mathrm{Re}\left[\underline{S}_s(\mathbf{X})\right]; \\ Q_s(\mathbf{X}) = \mathrm{Im}\left[\underline{S}_s(\mathbf{X})\right]. \end{cases} \quad (18)$$

Thus, by using equations (15), (16) and (18), it is possible to determine the correlation between the argument (control vector **X**) and the values for the criteria functions included in the statement of the problem on control over the parameters of a DEN with SCD (2).

As shown in works [8, 9], it is most expedient to solve a problem on multi-criteria optimization in the form (2) by applying a method of the approximation to a utopian point in the criteria space. According to this method, the problem (1) is solved in 2 steps:

Step 1. The result of finding a minimum for each criteria functions, included in the problem (2) statement, is the derived coordinates for ideal point $Q_{ut} = (\mathrm{tg}\varphi_{ut}, L_{\Delta Uut}, L_{k2Uut})$ in the criteria space $\mathbf{Q} \subset \mathbb{R}^3$. Given the considerably complex and cumbersome expressions describing the criteria functions in the statement of problem (2), it is most expedient, to find the coordinates for a utopian point, to use one of the known numerical methods for solving the problems on the conditional optimization of the function of numerous variables.

Step 2. Solving the problem on the scalar optimization (minimization) of the distance ρ between the ideal point Q_{ut} and a Pareto-optimal set of solutions yields the ultimate solution to the optimization problem $\mathbf{X}^*$ (an optimal control vector) in the control space $\Omega \subset \mathbb{R}^3$.

Work [10] noted that finding the ultimate solution to the problems similar to (2) is most expedient to be carried out by minimizing the Chebyshev distance from the utopian point to the Pareto-optimal set of solutions. According to this approach, the expression for finding the vector of optimal control $\mathbf{X}^*$ takes the following form:

$$\begin{cases} F(\mathbf{X}) = \max\left\{ \begin{array}{l} \dfrac{\mathrm{tg}\,\varphi(\mathbf{X}) - \mathrm{tg}\,\varphi_{ut}}{\zeta_1}, \\ \dfrac{L_{\Delta U}(\mathbf{X}) - L_{\Delta U ut}}{\zeta_2}, \\ \dfrac{L_{k2U}(\mathbf{X}) - L_{k2U ut}}{\zeta_3} \end{array} \right\} \to \min; \\ \mathbf{X} \in \Omega, \end{cases} \quad (19)$$

where ζ_1, ζ_2, ζ_3 are the weight coefficients, taking into consideration the relative importance of each criterion.

To solve a problem on the scalar optimization of the function of many variables (19), as well as for the case of a problem on finding the coordinates of a utopian point, it is advisable to use one of the numerical methods.

Based on the derived solution to the problem of multicriteria optimization, we built a structural diagram for the ACS over the level of electric power quality indicators in a DEN with SCD, which is shown in Fig. 3.

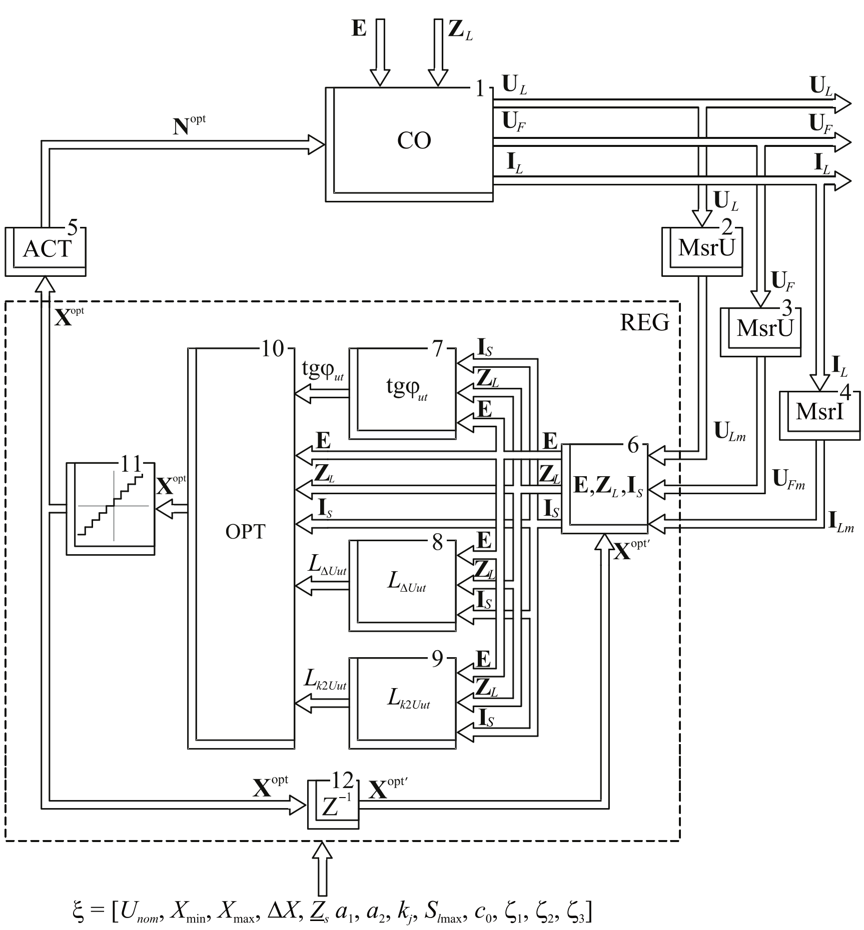


Fig. 3. Structural circuit of ACS over the level of electric power quality indicators in a DEN with SCD

In Fig. 3: $\mathbf{E}=[\underline{E}_A, \underline{E}_B, \underline{E}_C]$ – vector of the complexes of emf of the power network; $\mathbf{Z}_L=[Z_{lAB}, Z_{lBC}, Z_{lCA}]$ – vector of complex resistances of an equivalent load, connected in line with the scheme of a «triangle» (according to Fig. 1); $\mathbf{U}_L=[\underline{U}_{AB}, \underline{U}_{BC}, \underline{U}_{CA}]$ – vector of complexes of linear voltages at the point where SCD connects to the equivalent load; $\mathbf{U}_F=[\underline{U}_A, \underline{U}_B, \underline{U}_C]$ – vector of complexes of phase voltages at the point where SCD connects to the equivalent load; $\mathbf{I}_L=[\underline{I}_{lA}, \underline{I}_{lB}, \underline{I}_{lC}]$ – vector of complexes of linear currents in phases *A*, *B*, *C* in a load circle; $\mathbf{U}_{Lm}=[\underline{U}_{ABm}, \underline{U}_{BCm}, \underline{U}_{CAm}]$ – vector of the measured values of the complexes of linear voltages at the point where SCD connects to the equivalent load; $\mathbf{U}_{Fm}=[\underline{U}_{Am}, \underline{U}_{Bm}, \underline{U}_{Cm}]$ – vector of the measured values of the complexes of phase voltages at the point where SCD connects to the equivalent load; $\mathbf{I}_{Lm}=[\underline{I}_{lAm}, \underline{I}_{lBm}, \underline{I}_{lCm}]$ – vector of the measured values of the complexes of linear currents in phases *A*, *B*, *C* in a load circle; $\mathbf{I}_{LS}=[\underline{I}_{sA}, \underline{I}_{sB}, \underline{I}_{sC}]$ – vector of the complexes of linear currents in phases *A*, *B*, *C* in a load circle; $\xi=[U_{nom}, X_{\min}, X_{\max}, \Delta X, \underline{Z}_s, a_1, a_2, k_j, S_{l\max}, c_0, \zeta_1, \zeta_2, \zeta_3]$ – vector of the setting parameters; U_{nom} – rated value of the linear voltage in a network; $X_{\min}$, $X_{\max}$ – minimum and maximum value of the SCD capacitive resistance (the minimum and maximum value of the control vector), respectively; ΔX – a step in the change of the SCD capacitive resistance (a step of control); $\underline{Z}_s$ – complex value of the phase resistance of the power supply network; $\mathbf{X}^{opt}=(X_{AB}^{opt}, X_{BC}^{opt}, X_{CA}^{opt})$ – optimal control vector; $\mathbf{N}^{opt}=(N_{AB}^{opt}, N_{BC}^{opt}, N_{CA}^{opt})$ – vector of the values for the numbers of SCD sections, corresponding to the optimum control vector $\mathbf{X}^{opt}$; $\mathbf{X}^{opt\prime}=(X_{AB}^{opt\prime}, X_{BC}^{opt\prime}, X_{CA}^{opt\prime})$ – optimal control vector found at the previous calculation step; REG – automated control unit; 1 – control object (DEN with SCD); 2, 3 – primary measuring transducers of a three-phase voltage (voltage transformers); 4 – primary measuring transducer of the load current (current transformer); 5 – controlling element, contactor, which executes phase-alternating switching of SCD sections; 6 – unit for computing the $\mathbf{Z}_L$, $\mathbf{I}_S$, $\mathbf{E}$ vectors according to formulae (5), (6), and (11), respectively; 7, 8, 9 – units for computing the coordinates for an utopian point $\mathrm{tg}\varphi_{ut}$, L_{DUut}, L_{k2Uut}; 10 – unit for computing the vector of optimal control $\mathbf{X}^{opt}$; 11 – unit for discretizing the values of capacitive resistances of the SCD phases; 12 – unit for the transport (temporal) delay of a signal by 1 discretization step.

The generalized algorithm for computing a vector of optimal control $\mathbf{X}^{opt}$ (the algorithm of a controller operation) is shown in Fig. 4 in the form of a flowchart.

In Fig. 4: 3 – procedure for determining $\mathbf{E}$, $\mathbf{Z}_L$ and $\mathbf{I}_S$ from formulae (5), (6), and (11), respectively; 4 – procedure for determining $\mathrm{tg}\varphi_{ut}$; 5 – procedure for determining L_{DUut}; 6 – procedure for determining L_{k2Uut}; 7 – procedure for determining the optimal control vector $\mathbf{X}^{opt}$.

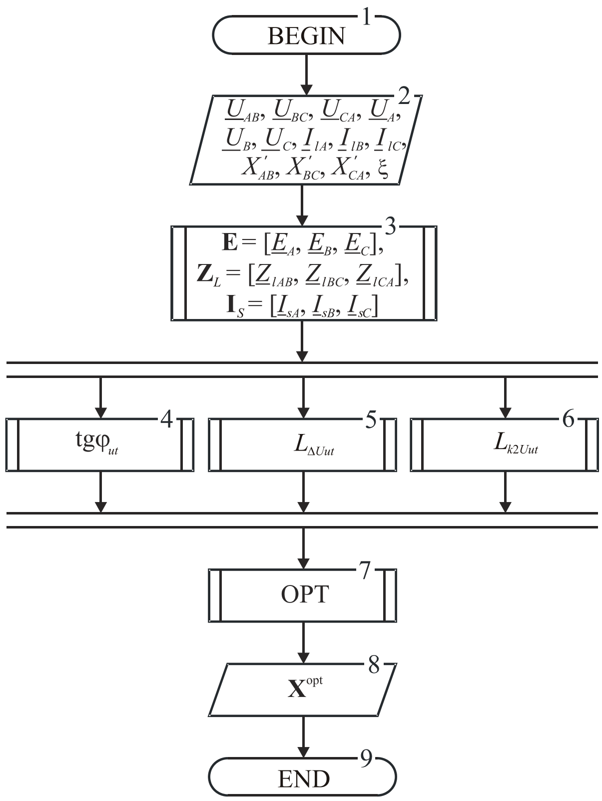


Fig. 4. Flowchart of the algorithm for computing an optimal control vector

Thus, the constructed structural diagram of the ACS over the level of electric power quality indicators in a DEN (Fig. 3), as well as the algorithm for determining a vector of optimal control according to the chosen method for solving the problem on multi-criteria optimization (2) (Fig. 4), make it possible to create an ACS computer model based on them, as well as define the effect of its application.

4. 2. Computer simulation model of the optimal system of automated control over the EQI level in an electrical distributing network

To study the operating modes of an ACS over the level of electric power quality indicators in a DEN with SCD, we constructed its computer simulation model in the MATLAB/Simulink programming environment. The generalized structural diagram of the specified ACS is shown in Fig. 5.

In Fig. 5: «EMF» – unit for setting a change in the system emf over time; «Load» – unit for setting the load resistance over time; «EDN» – model of a DEN with SCD; «MPM» – model of the EQI mode parameter meter; «optimal ACS» – model of the optimal ACS over the mode parameters and the level of EQI, which is based on the constructed algorithm for computing the optimal control vector $\mathbf{X}^{opt}$; «TN» – model of a voltage transformer; «TA» – model of a current transformer; «tgF», «DU1», «K2U» – virtual oscillographs, reflecting a change in the tgφ, DU_1, k_{2U} parameters over time.

A model of the «EDN» unit is shown in Fig. 6.

The computer model of the «EDN» unit, shown in Fig. 6, was born on the basis of the found ratios (3) to (14), which describe the correlation between the input and output parameters of the control object.

It should be noted that in order to simplify computer simulation, we did not build a separate computer model for the controlling element (since the values of the SCD capacitive resistances and the SCD's sections numbers are linked via constant magnitudes, while the delays in time introduced by the controlling element can be ignored). Therefore, the control signal used in a given computer model of a DEN with SCD is the $\mathbf{X}^{opt}$ vector rather than $\mathbf{N}^{opt}$.

Underlying the operation of an «optimal ACS» unit model is the developed structural diagram of the ACS over the modes of a DEN with SCD for a distributing electric network with a voltage of 10 kV, as well as the proposed algorithm for computing the optimal control vector $\mathbf{X}^{opt}$. The computer simulation model of the «optimal ACS» unit is shown in Fig. 7.

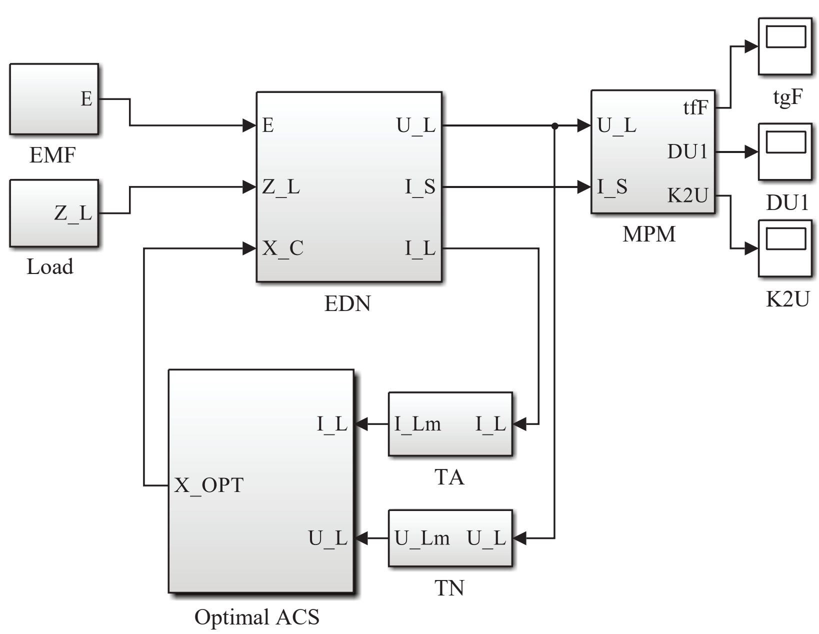


Fig. 5. Generalized computer simulation model of an ACS over the level of electricity quality indicators in a DEN with SCD in the MATLAB/Simulink programming environment

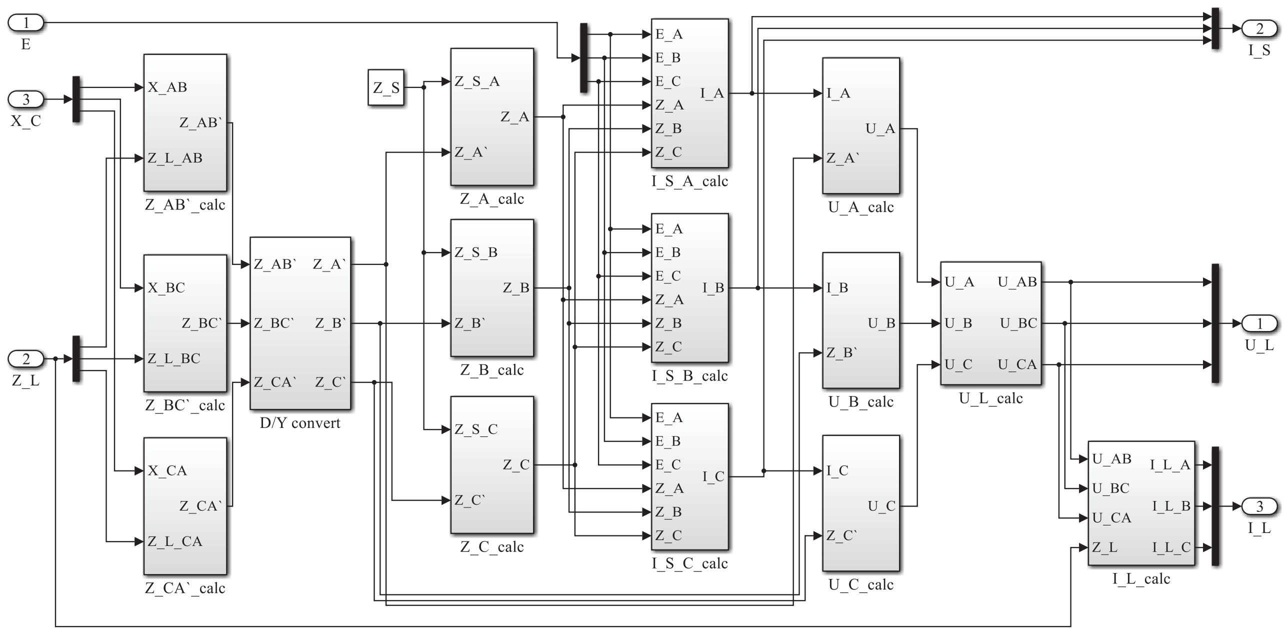


Fig. 6. A model of the «EDN» unit in the MATLAB/Simulink programming environment

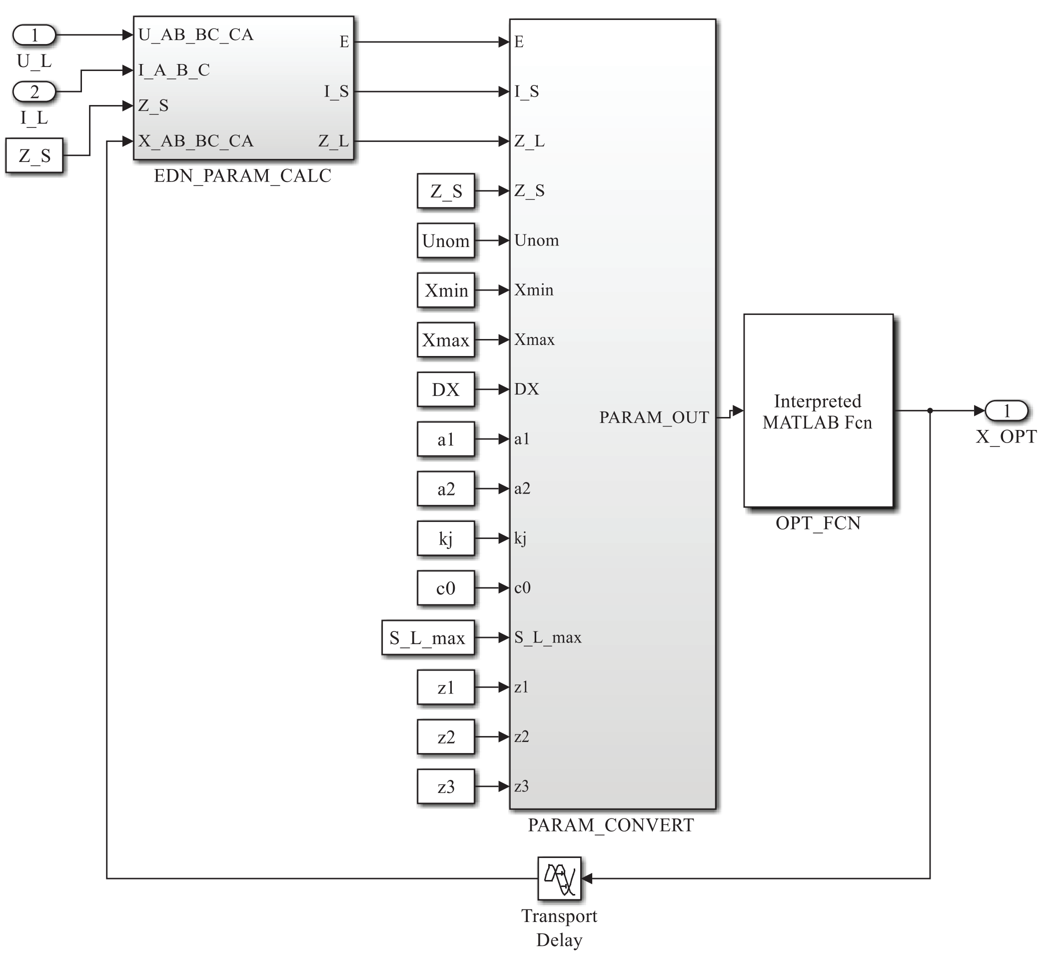


Fig. 7. A computer simulation model of the «optimal ACS» unit in the MATLAB/Simulink programming environment

The model shown in Fig. 7 consists of the following main units: «EDN_PARAM_CALC» – unit for computing the values for the $\mathbf{E}$, $\mathbf{Z}_L$ and $\mathbf{I}_S$ vectors; «PARAM_CONVERT» – unit for converting the model parameters; «Transport Delay» – unit of a transmission delay of the signal by 1 simulation step; «OPT_FCN» – the Interpreted MATLAB Function unit whose software implements the constructed algorithm for calculating the optimal control vector $\mathbf{X}^{opt}$.

5. Results of simulating the operation of an optimal system of automated control over the EQI level

To study the effect achieved by using the designed ACS, we carried out a comparative computer simulation of the operation of the constructed and basic ACSs for a DEN whose structural diagram is shown in Fig. 8.

The ACS described in work [9] was chosen as the basic one, which is based on a solution to the problem of multi-criteria optimization (1).

The results of a comparative computer simulation for the case of the constructed and basic ACSs over mode parameters are shown in Fig. 9–11.

Table 1 gives the results of processing the data from the computer simulation of the basic and constructed ACSs over the mode parameters of a DEN with SCD.

Table 1 shows that the values of the integrated probability to enter the normally permissible ranges of ΔU_1 and k_{2U} both for the basic ACS and for that proposed in the current work meet the acting regulatory requirements. However, when applying the developed ACS, the mathematical expectation of the value for an established voltage deviation $M[\Delta U_1]$ appears to be 6.9 % greater than that of the basic ACS, while the mathematical expectation of the value for a coefficient of voltage asymmetry in reverse sequence $M[k_{2U}]$ is 9.6 % less. Such results are due to choosing, as the criteria functions for problem (2), the dependences describing the negative influence of the established deviation ΔU_1 and the voltage asymmetry coefficient in reverse sequence k_{2U} on the operation of a DEN, which in general is not equal to each of the specified EQIs.

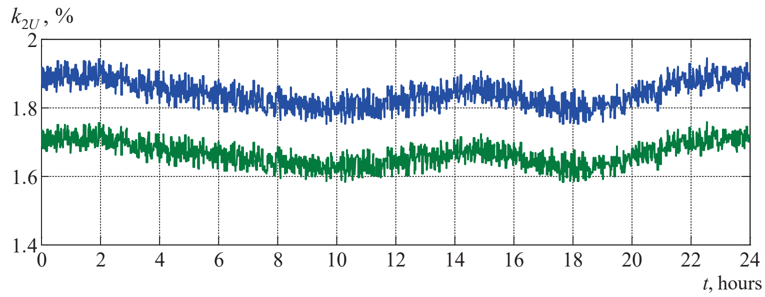


Fig. 10. Diagrams of change in k_{2U}: *a* — basic ACS; *b* — developed ACS

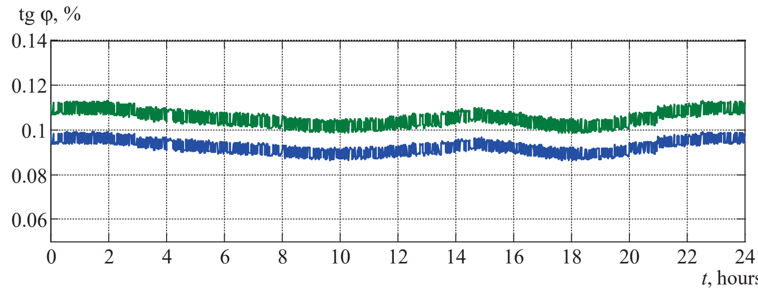


Fig. 11. Diagrams of change in tgφ: *a* — basic ACS; *b* — developed ACS

Table 1

Results of data processing of the computer simulation modeling of the basic and developed ACS by the DEN regime with the SCD

No. of entry	Indicator	Basic ACS	Developed ACS
1	Mathematical expectation of the value for a reactive power factor, M[tgφ], %	0.092	0.105
2	Mathematical expectation of the value for an established voltage deviation, $M[\Delta U_1]$, %	4.198	4.486
3	The integrated probability for the value of an established deviation of voltage to enter the range of normally acceptable values, $P[-5<\Delta U_1<5]$, a. u.	1	1
4	Mathematical expectation of the value for a voltage asymmetry coefficient in reverse sequence, $M[k_{2U}]$, %	1.841	1.664
5	The integrated probability for the value of a voltage asymmetry coefficient to enter in a reverse sequence, $P[k_{2U}<2]$, a. u.	1	1

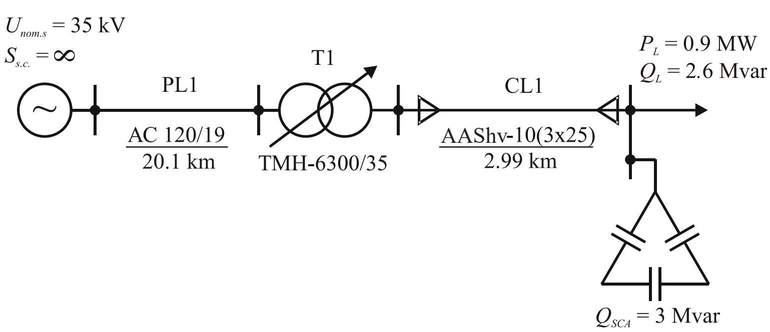


Fig. 8. Structural diagram of a DEN with SCD

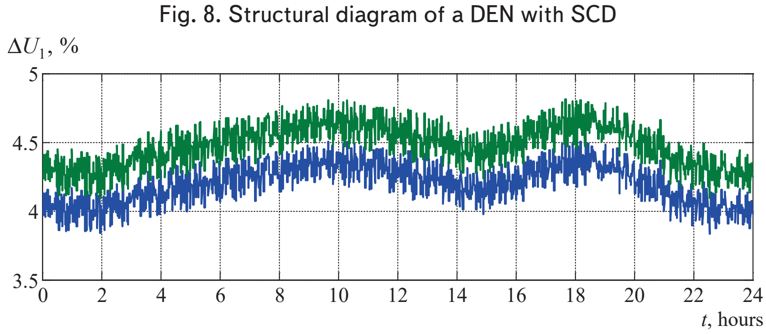


Fig. 9. Diagrams of change in ΔU_1: *a* — basic ACS; *b* — developed ACS

It should be noted that one observes, for the case of the developed ACS, an insignificant increase (by 14.3 %) in the value of a reactive power factor tgφ.

6. Discussion of results of studying the process of automated control over the electricity quality indicators in a DEN

The efficiency and cost-effectiveness of DEN operation are largely determined by the level of EQIs. First of all, it concerns those EQIs that normalize the levels of the established deviation and voltage asymmetry in a DEN. Given this, the development of an ACS of the DEN regime parameters, which would ensure minimizing the negative impact of the inflated values on the operation of an electric network, is an important scientific and practical task.

The existing optimal ACSs over the mode of a DEN with SCD [8, 9], which are based on the solution to a multi-criteria optimization problem, ensure the minimization of values of the established voltage deviation ΔU_1 and a voltage asymmetry coefficient k_{2U} in reverse sequence. This approach to control does not take into consideration the inequivalence of the negative effects exerted by the inflated values of the established deviation and the asymmetry of voltages. In order to eliminate a given drawback, this work has proposed using, as the criteria functions for a problem on the multi-criteria optimization of the EQI levels in a DEN, the dependences, which assess the level of the negative influence exerted by the inflated values of the deviation and asymmetry of voltages on the DEN operation.

As shown by the results of computer simulation of the operation of the basic ACS and the ACS proposed in this work (Fig. 9–11, Table 1), the developed ACS demonstrated a 6.9 % greater mathematical expectation $M[\Delta U_1]$ compared to that of the basic ACS, while the mathematical expectation $M[k_{2U}]$ was 9.6 % less. Such results are predetermined primarily by the that the chosen criteria functions for a multicriteria optimization problem (2) were the dependences that determine the level of a negative influence exerted by the established deviation and the asymmetry of voltages, which, in a general case, is not equivalent for the specified EQIs. Given this, it can be concluded that the implementation of the ACS over the level of electric power quality indicators, proposed in this work, can potentially lead to a decrease in the economic losses caused by the inflated values of the established voltage deviation ΔU_1 and the coefficient of voltage asymmetry in reverse sequence k_{2U} in a DEN.

In terms of the theory of automatic control, a DEN is a rather complex multi-dimensional nonlinear control object, which is exposed to a significant number of random disturbances. Therefore, in order to simplify the computer simulation model of the ACS over the level of electricity quality indicators in a DEN, its construction involved a series of assumptions:

– the absence of random disturbances in the measuring channels of current and voltage;

– the absence of time delays by a controlling element (which is only valid for the case of a contactless device to switch the SCD sections);

– the lack of time delays in the current and voltage measurement channels;

– the linearity of a volt-ampere characteristic of the equivalent resistance of the power system;

– the electric loads and SCD are represented in the form of equivalent active and reactive resistances.

The above assumptions introduce a certain level of error to the computer simulation model and must be taken into consideration in the process of practical implementation of the developed ACS.

The disadvantage of the proposed approach to automatic control is a certain complexity when choosing the weight coefficients ζ_1, ζ_2, ζ_3, whose values are selected empirically during the operation of the developed ACS. More promising is the approach according to which the values for these weight coefficients would be determined through the use of certain adaptive algorithms, taking into consideration additional information about the operational parameters of a distributing electric network.

The reported results of our research are the advancement of the approach, proposed in works [8, 9], to the construction of an ACS over the level of electricity quality indicators in a DEN. Further studies in the field of developing similar ACSs are planned for electrical networks of other voltage classes.

7. Conclusions

1. Our analysis has revealed that in order to improve the operational efficiency of an ASC over the level of electricity quality indicators in a DEN, based on the solution to the problem of multicriteria optimization using the method of approaching a utopian point, it is necessary to use, as the criteria functions, the dependences that determine the negative influence exerted by the established deviation and the asymmetry of voltages on the DEN operation. Such an approach to automatic control makes it possible to take into consideration the inequivalence of the negative impact exerted by the specified EQIs on DEN operation.

2. The results of computer-simulation modeling of the operation of the ACS over the level of electric power quality indicators in a DEN with a voltage of 10 kV have confirmed the correctness of our theoretical study. Thus, for the case of the developed ACS, the mathematical expectation of the value for an established voltage deviation $M[\Delta U_1]$ was 6.9 % greater than that of the basic ACS while the mathematical expectation of the value for a coefficient of voltage asymmetry $M[k_{2U}]$ was 9.6 % less. Such results are predetermined by considering, in the statement of a control problem, the inequality of the negative influence exerted by the established deviation and the asymmetry of voltage on DEN operation. An analysis of the simulation results reveals that the implementation of the ACS over the level of electric power quality indicators, proposed in this work, can potentially lead to a decrease in the economic losses caused by the established deviation and the asymmetry of voltage in DENs.

References

1. Popova, I., Nesterchuk, D., Popryadukhin, V. (2017). An influence analysis of non-symmetric loading upon operation modes of three-phase asynchronous electric motor. Visnyk KhNTUSH im. P. Vasylenka. Tekhnichni nauky, 186, 85–87.
2. Zimann, F. J., Batschauer, A. L., Mezaroba, M., Neves, F. A. S. (2019). Energy storage system control algorithm for voltage regulation with active and reactive power injection in low-voltage distribution network. Electric Power Systems Research, 174, 105825. doi: https://doi.org/10.1016/j.epsr.2019.04.003
3. Zajkowski, K. (2020). Two-stage reactive compensation in a three-phase four-wire systems at nonsinusoidal periodic waveforms. Electric Power Systems Research, 184, 106296. doi: https://doi.org/10.1016/j.epsr.2020.106296
4. Panda, A. K., Patnaik, N. (2017). Management of reactive power sharing & power quality improvement with SRF-PAC based UPQC under unbalanced source voltage condition. International Journal of Electrical Power & Energy Systems, 84, 182–194. doi: https://doi.org/10.1016/j.ijepes.2016.05.010
5. Pană, A., Băloi, A., Molnar-Matei, F. (2020). New method for calculating the susceptances of a balancing capacitive compensator for a three-phase four-wire distribution network. International Journal of Electrical Power & Energy Systems, 115, 105414. doi: https://doi.org/10.1016/j.ijepes.2019.105414

6. Duarte, S. N., Souza, B. C., Almeida, P. M., Araujo, L. R., Barbosa, P. G. (2020). Control algorithm for DSTATCOM to compensate consumer-generated negative and zero sequence voltage unbalance. International Journal of Electrical Power & Energy Systems, 120, 105957. doi: https://doi.org/10.1016/j.ijepes.2020.105957
7. Zeng, X. J., Zhai, H. F., Wang, M. X., Yang, M., Wang, M. Q. (2019). A system optimization method for mitigating three-phase imbalance in distribution network. International Journal of Electrical Power & Energy Systems, 113, 618–633. doi: https://doi.org/10.1016/j.ijepes.2019.05.038
8. Plieshkov, P. H., Zinzura, V. V., Plieshkov, S. P. (2019). Automatic control of electrical distribution network mode with the voltage unbalance. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 3, 83–91. doi: https://doi.org/10.29202/nvngu/2019-3/10
9. Taranukha, M. S., Teluyta, R. V., Zinzura, V. V. (2015). Optimal control of reactive load modes in conditions of asymmetry of voltage electricity distribution networks. Visnyk Natsionalnoho tekhnichnoho universytetu «Kharkivskyi politekhnichnyi instytut». Zbirnyk naukovykh prats. Tematychnyi vypusk: Problemy udoskonalennia elektrychnykh mashyn i aparativ. Teoriya i praktyka, 42, 62–66. Available at:http://repository.kpi.kharkov.ua/handle/KhPI-Press/19801
10. Zinzura, V. (2012). The justification of the solution of the problem of multicriteria optimization of voltage control in power networks. Zbirnyk naukovykh prats Kirovohradskoho natsionalnoho tekhnichnoho universytetu. Tekhnika v silskohospodarskomu vyrobnytstvi, haluzeve mashynobuduvannia, avtomatyzatsiya, 25 (1), 350–360. Available at: http://dspace.kntu.kr.ua/jspui/handle/123456789/1388

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SYNTHESIS AND INVESTIGATION OF THE CONTROL SYSTEM FOR THE PROCESS OF CARBON ARTICLE MOLDING

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Одним з найбільш енергоємних виробництв є виробництво вуглецевих виробів, тому підвищення ефективності даного виробництва є актуальною науково-технічною задачею. Одним із шляхів розв'язання поставленої задачі є створення сучасної системи керування виробництвом.

У роботі розглядаються питання створення системи керування одним з визначальних технологічних процесів виробництва вуглецевих виробів – процесом їх формування. В основу роботи системи керування покладений критерій оптимальності на основі питомої собівартості продукції з урахуванням показників її якості. Як метод керування використовується МРС-керування (Model Predictive Control). Результати проведеного дослідження залежності критерія оптимальності від параметрів налаштувань МРС-регулятора дозволили визначити оптимальні значення горизонтів прогнозування та керування, які забезпечують мінімізацію питомої собівартості продукції. Розроблена структура запропонованої системи керування у середовищі Simulink, що дозволяє досліджувати дану систему керування шляхом комп'ютерного моделювання.

Дослідження ефективності запропонованої системи керування процесом формування вуглецевих виробів здійснювалось шляхом порівняння якості керування даної системи та системи, яка використовує класичний ПІД-закон керування. З цією метою у середовищі Simulink синтезовано трьохконтурну систему керування на основі ПІД-регуляторів. Налаштування кожного з регуляторів проводилось за методом Пауела на мінімальне значення інтегрального критерію. Результати порівняльного дослідження продемонстрували, що на кожному циклі роботи значення критерію оптимальності у системі керування з МРС-регулятором на 8,8 % менше, ніж у системі з ПІД-регуляторами при однакових показниках якості продукції. Це говорить про покращення техніко-економічних показників процесу формування. Особливого значення ця обставина набуває з урахуванням циклічності технологічного процесу формування вуглецевих виробів

Ключові слова: виробництво вуглецевих виробів, процес формування, гідравлічний прес, система керування, критерій оптимальності, МРС-керування

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1. Introduction

The properties of graphite products, in particular their high thermal stability, electrical conductivity, and mechanical strength [1–4] resulted in their widespread use in various branches of industrial production. At present, they are used in steelmaking, ferroalloy electro arc furnaces at metallurgical and machine-building enterprises, as the cathodes and