UDC 621.565.83
DOI: 10.15587/1729-4061.2026.354701

DETERMINING WEIGHT COEFFICIENTS IN THE CONTROL SYSTEM FOR A SYMMETRY-COMPENSATING DEVICE USING A FUZZY LOGIC APPARATUS

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This study investigates processes of automatic control over parameters of the distribution network mode at a voltage of 6–10 kV with a sharply changing asymmetric load.

The task addressed relates to the compromised efficiency of existing systems for automatic control over symmetry-compensating devices, which are based on multi-criteria optimization methods with unchanged weight coefficients. Such systems continue to give maximum priority to reducing the steady-state voltage deviation even if it meets regulatory requirements. This leads to incomplete utilization of regulating reserve of the symmetry-compensating device.

The system of automatic control over the symmetry-compensating device has been improved by integrating a fuzzy controller into its structure. This controller changes the values of weight coefficients in the objective function depending on the current values of the network mode parameters. The computer simulation has confirmed the effectiveness of the designed system, which provided a reduction in the mathematical expectations of the reactive power factor M[tanφ] by 13.9% and the voltage unbalance factor M[k2U] by 8.5% compared to the baseline.

The increase in the efficiency of the control system is explained by its ability to adaptively change the weight coefficients. Thus, if there is a margin for the steady-state voltage deviation, the fuzzy controller reduces the weight coefficient that meets this criterion, directing the regulating resource of the symmetrical-compensating device to increase the level of reactive power compensation and reduce the level of asymmetry.

A feature of the designed control system is the use of the levels of approximation of the current values of the steady-state deviation and voltage asymmetry to their regulatory permissible limits as input variables in the fuzzy controller.

The designed automatic control system could be used in distribution electrical networks with a voltage of 6–10 kV at a sharply changing asymmetrical load

Keywords: symmetry-compensating device, fuzzy logic, multi-criteria optimization, automatic control system

Received 18.12.2025
Received in revised form 02.03.2026
Accepted date 11.03.2026
Published date 30.04.2026

How to Cite: *Plieshkov, P., Zinzura, V., Petrova, K., Soldatenko, V., Nekrasov, A. (2026). Determining weight coefficients in the control system for a symmetry-compensating device using a fuzzy logic apparatus. Eastern-European Journal of Enterprise Technologies, 2 (2 (140)), 85–93. https://doi.org/10.15587/1729-4061.2026.354701*

1. Introduction

At the current stage of evolution of the electric power industry, the task to increase energy efficiency is becoming particularly urgent. For distribution networks with a voltage of 6–10 kV, from which industrial and municipal consumers are powered, the typical mode of operation is under a sharply changing and asymmetrical electrical load. This causes an increase in active power losses in the network elements and the emergence of voltage asymmetry, which negatively affects electrical equipment operation.

One of the common technical means for compensating reactive power and reducing voltage asymmetry in distribution networks is symmetry-compensating devices (SCDs). Most existing automatic control systems (ACSs) for such devices do not fully take into account their multifunctional impact on the parameters of the distribution electrical network. The control algorithms for such ACSs enable the minimization of only one indicator, while other parameters of the mode are stabilized within the permissible range of values.

At the same time, existing ACSs, which are based on multi-criteria optimization methods, use time-invariant weighting factors. This approach to constructing ACSs ensures compliance with regulatory requirements for electricity quality. However, it does not make it possible to fully realize the existing technical capabilities of ACS to simultaneously improve electricity quality and increase the level of reactive power compensation.

Even if the voltage deviation value is within the permissible range, such an ACS continues to reduce its level. This significantly limits the ACS's capabilities to increase the level of reactive power compensation and minimize asymmetry.

Designing adaptive optimal ACSs with real-time variable weighting factors could increase the degree of use of SCD regulatory capabilities and thereby enable increased energy efficiency of the distribution electrical network.

Therefore, research aimed at implementing optimal ACS for a symmetry-compensating device with adaptive change in weighting factors is relevant.

2. Literature review and problem statement

Results of designing ACS for static capacitor banks based on a programmable logic controller are reported in [1]. It is shown that such a system provides an increase in the power factor of inductive loads. However, the issues related to the simultaneous minimization of voltage deviation levels, voltage asymmetry, and reactive power compensation remain unresolved. A likely reason is the difficulties associated with the limited functionality of the basic control algorithms.

An option for overcoming these difficulties may be the use of reference adaptive models or artificial neural networks. This approach was employed in [2, 3]. It is shown that these methods have improved dynamic characteristics and the ability to adapt. However, the issues of their practical use in branched distribution networks with a variable configuration remain unresolved. The reason is the need for high accuracy in identifying the control object [2], as well as the requirement for large amounts of training data [3], which are practically impossible to provide under real operation conditions.

The use of fuzzy logic mathematical apparatus, proposed in [4] for high-voltage networks, makes it possible to bypass the complexity of mathematical modeling. However, the issue of controlling the level of voltage asymmetry in low-voltage networks remains unresolved. In [5, 6], the use of fuzzy and neuro-fuzzy logic for controlling static synchronous compensators to reduce voltage deviation and asymmetry is considered. However, the reason for the limited use of such devices is their high cost, which makes the relevant research impractical for mass implementation in distribution electrical networks with a voltage of 6–10 kV.

Other approaches, such as controlling inverters of solar power plants [7] or algorithms that require comprehensive information about the network topology [8], also face problems. A likely reason is the fundamental impossibility of implementing automatic network control in the absence of solar insolation [7] and the impossibility of obtaining accurate topology parameters in real time [8].

An effective option for overcoming the described difficulties is the use of the mathematical apparatus of multi-criteria optimization for constructing an ACS for symmetry-compensating devices. This approach was used in works [9, 10]. It is shown that this makes it possible to achieve simultaneous minimization of the levels of reactive power consumption, steady-state deviation and voltage asymmetry. However, the issues of rational use of the free regulatory resource of the ACS are unresolved in those works. A likely reason is the fundamental impossibility of the system to respond to the dynamics of the network due to the invariance of the weight coefficients over time. This leads to the fact that the system spends resources on optimizing parameters that already meet the regulatory requirements with a margin.

An option for overcoming this problem is dynamic adaptation of weight coefficients. This approach was used in [11], in which the fuzzy logic apparatus based on the load importance coefficient was applied for adaptation. However, the reason for the insufficient efficiency of this method is the heuristic nature of the importance coefficient, which depends on the reliability category of the consumer and does not take into account instantaneous changes in network parameters. Even when the voltage deviation of priority consumers corresponds to the norm, the ACS [11] retains the advantage of this criterion, which makes it impossible to reorient it to minimize other indicators.

Therefore, an unsolved scientific problem is the inability of existing optimal ACSs for symmetry-compensating devices to flexibly adapt to changes in the mode parameters through the use of static or heuristic priority settings.

All this gives grounds to argue that it is advisable to conduct a study aimed at devising a method for determining adaptive weighting coefficients for the automatic control system for a symmetry-compensating device. It should take into account the current level of approximation of electricity quality indicators to regulatory limits and enable rational redistribution of the available control resource.

3. The aim and objectives of the study

The purpose of our study is to devise a technique for determining the weight coefficients of the automatic control system for a symmetry-compensating device, which takes into account the current level of approximation of the electricity quality indicators to the regulatory limits. This will make it possible to optimally use the reserve power of equipment SCD to simultaneously improve the electricity quality indicators and increase the level of reactive power compensation.

To achieve the goal, it is necessary to solve the following tasks:

– to justify the composition of the input linguistic variables of the fuzzy controller and devise a rule base for calculating the weight coefficients that determine the priority of the optimization criteria;

– to build a simulation model of the automatic control system for the symmetry-compensating device, in which the algorithm for adaptive determination of weight coefficients is implemented;

– to conduct a study on the effect of using the designed automatic control system for the symmetry-compensating device using the method of computer simulation.

4. The study materials and methods

The object of our study is the processes of automatic control over parameters of the distribution electric network mode with a voltage of 6–10 kV under a sharply changing asymmetric load.

The principal hypothesis assumes that the use of optimal SCD ACS with weight coefficients that do not change over time limits the possible level of reactive power compensation. At the same time, adaptive change of these coefficients depending on the level of approach of the mode parameters to the maximum permissible values makes it possible to maximize the level of reactive power compensation. This, in turn, makes it possible to increase the energy efficiency of the distribution electric network.

The following assumptions are adopted in the work: a three-phase three-wire electric network with an isolated neutral is considered, electrical loads are modeled as sources of active and reactive power with a random component. In addition, the speed of the SPC controlling elements is considered sufficient for working out control influences under quasi-steady modes.

To solve the tasks, the following methods were used:

– fuzzy set theory – to devise a technique for adapting weighting coefficients that determine the priority of criteria in a multi-criteria optimization problem;

– multi-criteria optimization methods – to determine optimal control influences (reactive resistances of the phases of SCD) according to the method of approaching the utopian point in the criteria space using the Chebyshev metric;

– computer simulation – to study the dynamics of ACS operation. Computer simulation of the operation of the designed automatic control system was carried out in the MATLAB software environment using the Simulink extension package.

5. Results of research on the effectiveness of an adaptive automatic control system for a symmetry-compensating device

5. 1. Justification of the composition of input linguistic variables and construction of a fuzzy controller rule base

As shown in [9, 10], the task of simultaneous minimization of deviation levels, voltage asymmetry, and the level of reactive power consumption should be formalized as a multi-criteria optimization problem. For distribution networks with a voltage of 6–10 kV, the statement of this problem takes the following form [9]:

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

where $\mathbf{X}=[X_{AB}, X_{BC}, X_{CA}]$ is the control vector consisting of the phase resistances of SCD; $P_s(\mathbf{X})$, $Q_s(\mathbf{X})$ are the values of the active and reactive powers consumed from the system; $\tan\boldsymbol{\varphi}(\mathbf{X})$ is the reactive power factor; $U_1(\mathbf{X})$ is the positive sequence voltage; $\Delta U_1(\mathbf{X})$ is the steady-state voltage deviation; U_{nom} is the nominal network voltage; $k_{2U}(\mathbf{X})$ is the negative sequence voltage unbalance factor; $U_2(\mathbf{X})$ is the effective value of the negative sequence voltage; Ω is the permissible control space determined by the SCD control limits.

In works [9, 10] it is shown that the solution to problem (1) is most expedient to carry out using the method of approximation to the utopian point in the criteria space. This method is implemented in two stages:

– first, by minimizing each of the criteria in problem (1), the coordinates of the utopian point $Q_{\mathbf{yT}}=(\tan\boldsymbol{\varphi}_{ut}, \Delta U_{1ut}, k_{2Uut})$ are determined;

– then the final solution to problem (1) is determined by solving the problem of minimizing the Chebyshev distance from the utopian point to the Pareto-optimal set of solutions. The expression for finding the final solution to problem (1) (the optimal control vector $\mathbf{X}^{opt}=\left[X_{AB}^{opt}, X_{BC}^{opt}, X_{CA}^{opt}\right]$) takes the following form:

$$\begin{cases} \max\begin{Bmatrix} w_{\tan\varphi}\left[\tan\varphi(\mathbf{X})-\tan\varphi_{ut}\right], \\ w_{\Delta U}\left[\Delta U_1(\mathbf{X})-\Delta U_{1ut}\right], \\ w_{k2U}\left[k_{2U}(\mathbf{X})-k_{2Uut}\right] \end{Bmatrix}\rightarrow\min; \\ \mathbf{X}\in\Omega, \end{cases} \tag{2}$$

where $w_{\tan\boldsymbol{\varphi}}$, $w_{\Delta U}$, w_{k2U} are weight coefficients that take into account the priority of each of the criteria.

To determine the weight coefficients $w_{\tan\boldsymbol{\varphi}}$, $w_{\Delta U}$, w_{k2U}, it is proposed to use the mathematical apparatus of fuzzy logic, in particular the Mamdani-type fuzzy inference algorithm. Although Sugeno-type systems have higher computational efficiency, the choice of the Mamdani algorithm is justified by the specificity of the problem being solved. Since the controller outputs are weight coefficients, not control influences, the algorithm forms conditions and conclusions exclusively in the form of linguistic terms. This approach makes it possible to directly transform expert experience into a set of logical rules, avoiding the need to apply mathematical equations at the output of the fuzzy controller.

As noted above, in [11], a heuristic parameter was used for fuzzy adjustment of weight coefficients – the load importance coefficient. A significant disadvantage of this approach is that it does not take into account instantaneous changes in the distribution network parameters. Thus, even if the voltage deviation at a node is within normal limits, the high value of the constant importance coefficient limits the possibilities of the AC system to increase the level of reactive power compensation.

To solve this problem, it is proposed to use objective parameters as input variables instead of a priori given value of the importance coefficient. As such parameters, it is most appropriate to choose the levels of approximation of the current values of the steady-state deviation and voltage asymmetry to their regulatory permissible limits.

Considering this, three parameters were selected as input linguistic variables of the fuzzy controller:

1. Load coefficient K_{load} characterizes the ratio of the actual load to the rated power of the elements of the distribution network (power transformer or power transmission line). K_{load} is determined from the following expression

$$K_{load}=\frac{\sqrt{P_i^2+Q_i^2}}{S_{nom}}, \tag{3}$$

where P_i, Q_i – current values of total active and reactive power of the load, respectively; S_{nom} – nominal full power of the power transformer (or line capacity). High K_{load} values shift the control priority towards reducing the steady-state voltage deviation and increasing the level of reactive power compensation.

2. Voltage deviation margin ΔU_{margin} characterizes the degree of approximation of the actual voltage deviation to the limits of the range of permissible values ΔU_{lim}. It is calculated from the following formula

$$\Delta U_{margin}=1-\frac{|\Delta U_{meas}|}{\Delta U_{lim}}, \tag{4}$$

where ΔU_{meas} is the measured value of the voltage deviation. The $\Delta U_{margin}=0$ value corresponds to reaching the permissible limit of the steady-state deviation, while $\Delta U_{margin}=1$ corresponds to the rated voltage value.

3. Voltage unbalance margin $k_{2Umargin}$ characterizes the degree of approximation of the actual voltage unbalance level k_{2Umeas} to the upper limit of the range of permissible k_{2Ulim} values. It is calculated from the following formula

$$k_{2Umargin}=1-\frac{k_{2Umeas}}{k_{2Ulim}}, \tag{5}$$

where k_{2Umeas} is the measured actual value of the negative sequence voltage unbalance coefficient; k_{2Ulim} is the largest permissible k_{2U} value.

In the process of designing the fuzzy controller, the ranges of change of the input and output variables were determined, as well as the corresponding membership functions. The characteristics of the input and output variables of the fuzzy controller are given in Table 1.

Table 1

Characteristics of input and output variables of a fuzzy controller

No. of entry	Designation	Parameter ID	Change range	Linguistic assessments (terms)
Input parameters of the model				
1	K_{load}	Load factor	0...1.2	Low (L)
				Normal (N)
				High (H)
2	ΔU_{margin}	Voltage deviation margin	0...1.0	Critical (C)
				Warning (W)
				Safe (S)
3	$k_{2Umargin}$	Voltage asymmetry margin	0...1.0	Critical (C)
				Warning (W)
				Safe (S)
Model output parameters				
1	$w_{\tan\varphi}$	Reactive power compensation criterion weight factor	0...1.0	Low (L)
				Medium (M)
				High (H)
2	$w_{\Delta U}$	Weight factor of the voltage deviation criterion	0...1.0	Low (L)
				Medium (M)
				High (H)
3	w_{k2U}	Weight factor of the stress asymmetry criterion	0...1.0	Low (L)
				Medium (M)
				High (H)

The scheme of a fuzzy controller that determines the values of weight coefficients is shown in Fig. 1.

Triangular and trapezoidal membership functions were chosen for the input and output fuzzy variables. The graphical representation of these functions is shown in Fig. 2–4.

The fuzzy controller is based on a rule base that provides adaptive change of weight coefficients. This base consists of 27 fuzzy production rules, a list of which is given in Table 2.

The rule base is based on the principle of rational use of the available regulation margin:

– if the ΔU_{margin} value is high, the system reduces the weight coefficient $w_{\Delta U}$, shifting the priority towards minimizing voltage asymmetry and increasing the level of reactive power compensation;

– when the ΔU_{margin} value approaches the limits of the permissible range, the weight coefficients take on values that provide compromise control.

– if ΔU_{margin} tends to zero, the task of reducing the level of steady-state voltage deviation takes on priority, and the influence of other criteria is limited.

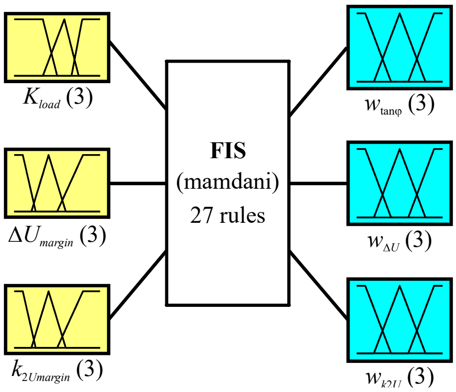

Fig. 1. Scheme of a fuzzy controller that determines the values of weight coefficients $w_{\tan\varphi}$, $w_{\Delta U}$, w_{k2U}

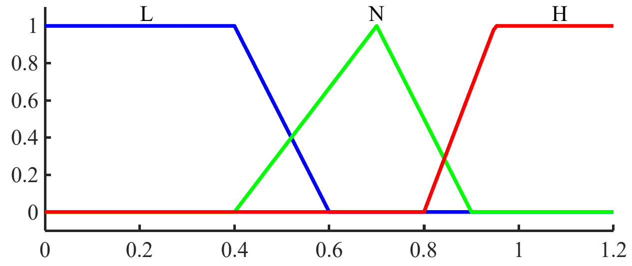

Fig. 2. Membership functions of the fuzzy input variable K_{load}: L – Low; N – Normal; H – High

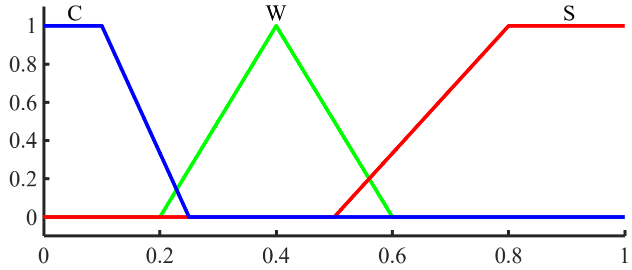

Fig. 3. Membership functions of fuzzy input variables ΔU_{margin} and $k_{2Umargin}$: C – Critical; W – Warning; S – Safe

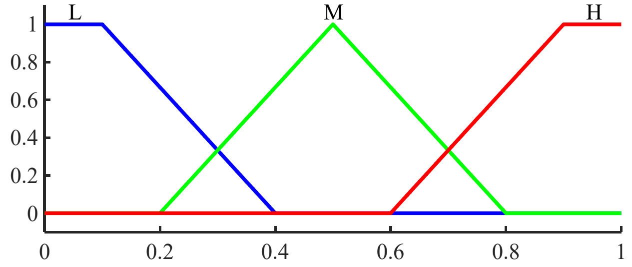

Fig. 4. Membership functions of fuzzy output variables $w_{\tan\varphi}$, $w_{\Delta U}$, w_{k2U}: L – Low; M – Medium; H – High

The response surface of the fuzzy controller $w_{\Delta U}=f(\Delta U_{margin}, K_{load})$ is shown in Fig. 5.

Table 2

Constructed fuzzy controller rule base

No. of entry	K_{load}	ΔU_{margin}	$k_{2Umargin}$	$w_{\tan\varphi}$	$w_{\Delta U}$	w_{k2U}
1	L	C	S	L	H	L
2	L	C	W	L	H	L
3	L	C	C	L	H	L
4	N	C	S	L	H	L
5	N	C	W	L	H	L
6	N	C	C	L	H	L
7	H	C	S	M	H	L
8	H	C	W	M	H	L
9	H	C	C	L	H	L
10	L	W	S	L	H	L
11	L	W	W	L	H	M
12	L	W	C	L	M	M
13	N	W	S	M	M	L
14	N	W	W	M	M	M
15	N	W	C	L	M	M
16	H	W	S	H	L	L
17	H	W	W	H	L	M
18	H	W	C	M	L	M
19	L	S	S	M	L	L
20	L	S	W	L	L	M
21	L	S	C	L	L	H
22	N	S	S	H	L	L
23	N	S	W	M	L	M
24	N	S	C	L	L	H
25	H	S	S	H	L	L
26	H	S	W	H	L	M
27	H	S	C	M	L	H

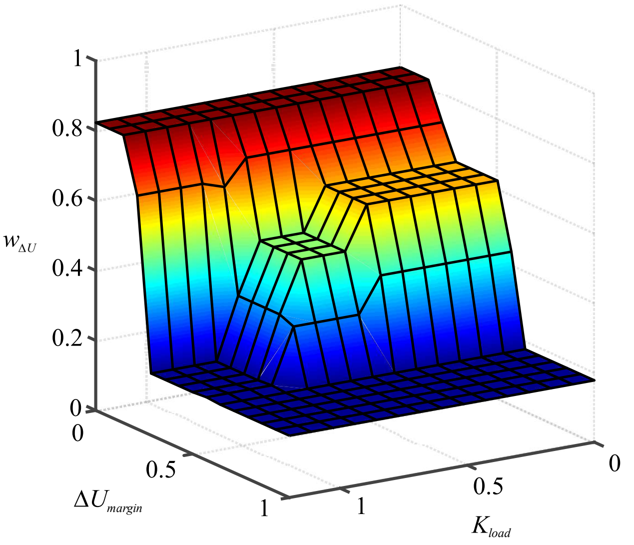

Fig. 5. Response surface of fuzzy controller $w_{\Delta U} = f(\Delta U_{margin}, K_{load})$

Analysis of Fig. 5 reveals that when $\Delta U_{margin} > 0.6$ the weight coefficient $w_{\Delta U}$ acquires minimum values. This rearranges the priority of the ASC to minimize voltage asymmetry and increase the level of reactive power compensation.

Defuzzification of the output variables is carried out by the center of gravity method, which ensures smooth changes in the values of the weight coefficients.

The values of the weight coefficients obtained at the output of the fuzzy controller are subject to normalization before their further use in the optimization module:

$$w'_{\tan\varphi}=\frac{w_{\tan\varphi}}{w_{\tan\varphi}+w_{\Delta U}+w_{k2U}}, \tag{6}$$

$$w'_{\Delta U}=\frac{w_{\Delta U}}{w_{\tan\varphi}+w_{\Delta U}+w_{k2U}}, \tag{7}$$

$$w'_{k2U}=\frac{w_{k2U}}{w_{\tan\varphi}+w_{\Delta U}+w_{k2U}}. \tag{8}$$

The normalization procedure according to formulas (6) to (8) guarantees that the sum of the values of all weight coefficients will be equal to unity. This is a prerequisite for the correct operation of the multi-criteria optimization algorithm since it enables proportional redistribution of control priorities.

5. 2. Construction of a computer simulation model of the automatic control system for a symmetry-compensating device

In order to verify the efficiency of the designed SCD ACS, its computer simulation model was built. The generalized structural diagram of this model is shown in Fig. 6.

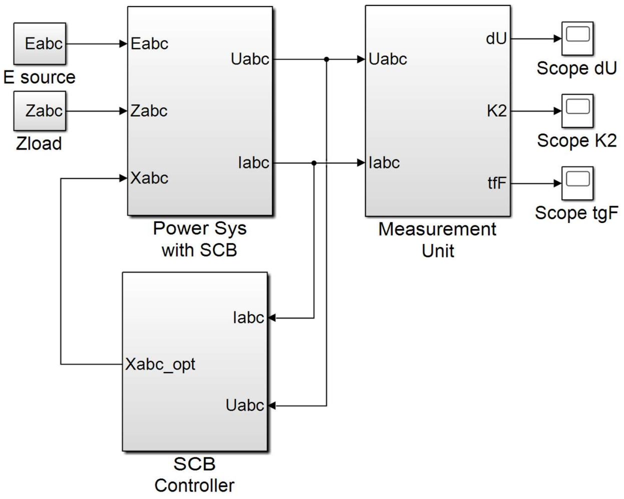

Fig. 6. Generalized structural diagram of the simulation model of the automatic control system for the symmetry-compensating device

The model consists of the following functional modules:

– "Power Sys with SCB" – a module that models the power part of the distribution network: a three-phase power source (Esource), a power transmission line, an asymmetric load (Zload) and SCB;

– "Measurement Unit" – a module for measuring the parameters of the distribution network mode (voltage deviation ΔU_1, the negative sequence voltage asymmetry factor k_{2U} and the reactive power factor $\tan\varphi$);

– "SCB Controller" – a module in which the developed algorithm for the operation of SCB is implemented. The input of this module is the values of the complexes of line voltages (Uabc) and phase currents (Iabc), and at the output the module forms a control vector (Xabc_opt).

The diagram of the "Power Sys with SCB" module is shown in Fig. 7.

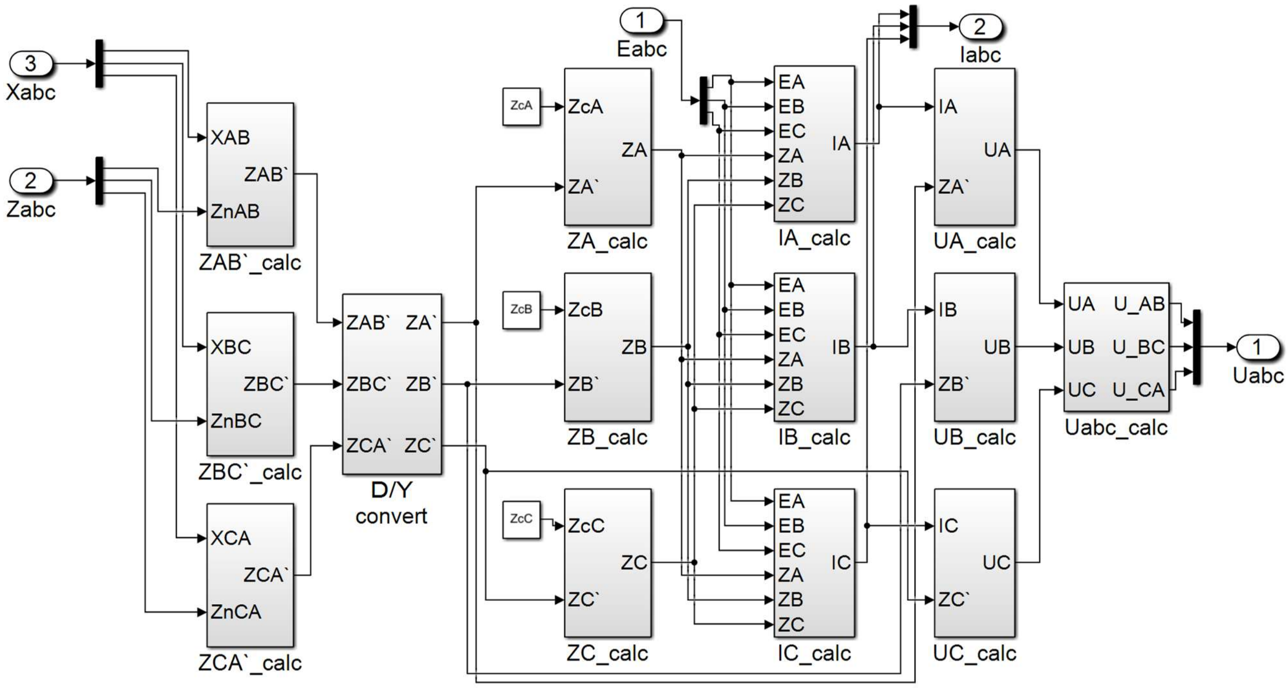

Fig. 7. Diagram of module «Power Sys with SCB»

The input signals of the “Power Sys with SCB” module model are the network voltage (E), load resistances (Zn), and capacitive resistances of the SCB (Xbk). The output signals of the module are the complexes of linear voltages of linear voltages (Uabc) and complexes of currents (Iabc). The relationship between the input and output parameters in the “Power Sys with SCB” module model is described using Kirchhoff’s laws.

The diagram of the “SCB Controller” module is shown in Fig. 8.

The algorithm of the “SCB Controller” module is as follows. In the “Param. Calc.” module, the current K_{load}, ΔU_1, k_{2U} values are calculated. Then, in the same module, the ΔU_{margin} and $k_{2Umargin}$ values are calculated according to formulas (4) and (5). To guarantee that the variables fall into the range [0, 1], “Saturation” type restriction modules are used. In the “Fuzzy Logic Controller” module, the fuzzy inference algorithm is implemented according to the developed rule base (Table 2). Receiving the input variables (K_{load}, ΔU_{margin}, $k_{2Umargin}$), the controller determines the vector of initial values of the weight coefficients $w_{\tan\varphi}$, $w_{\Delta U}$, and w_{k2U}. Next, the procedure for normalizing the output variables is performed according to formulas (6) to (8) using arithmetic sum and division modules. After that, the normalized $w'_{\tan\varphi}$, $w'_{\Delta U}$, w'_{k2U} values are sent to the “ACS_module” calculation module. In this module, at each step of the simulation, the multi-criteria optimization problem (1) is solved by the method of approaching the utopian point in the criteria space using the Chebyshev metric. The output signal of the “ACS_module” module is the optimal control vector $\mathbf{X}^{opt}$.

Thus, the computer simulation model built makes it possible to conduct research into the operating modes of the distribution electrical network with SCD and to assess the effectiveness of the proposed ACS.

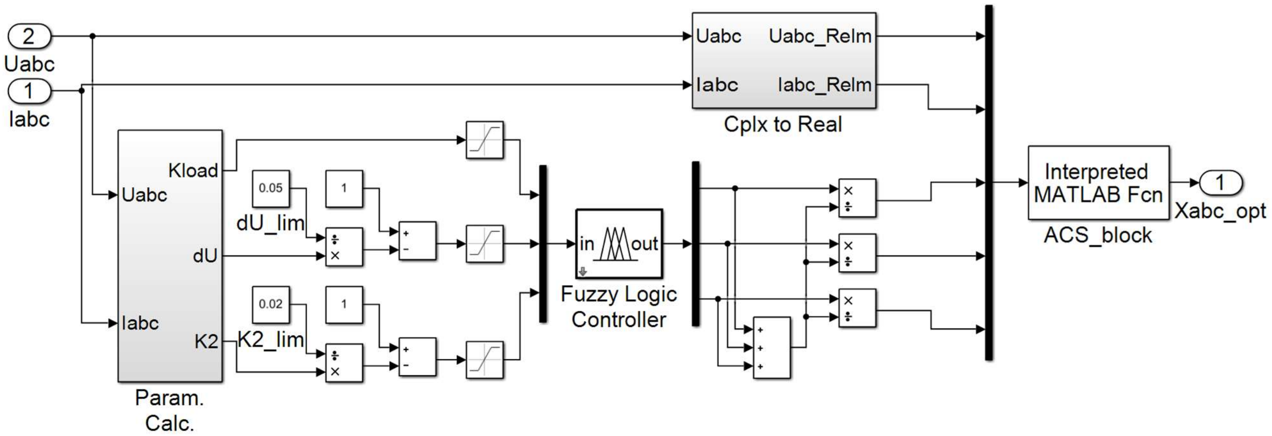

Fig. 8. Diagram of module «SCB Controller»

5. 3. Analyzing the efficiency of the designed automatic control system by computer simulation

The efficiency of the proposed ACS was assessed by comparative modeling using the simulation model built. The control system described in [9] was chosen as the basic ACS for comparison. To simulate the operation of the basic ACS, the fuzzy controller module was replaced by sources of constant signals. Simulation modeling of the operation of the basic and designed ACS was carried out over a time period of 24 h with a sampling interval of 30 s. In both cases, the same active and reactive load schedules were used, which are typical for industrial consumers with pronounced morning and evening peaks.

The simulation results are shown in Fig. 9–11.

The results of comparing the performance of the basic and designed ACS are given in Table 3.

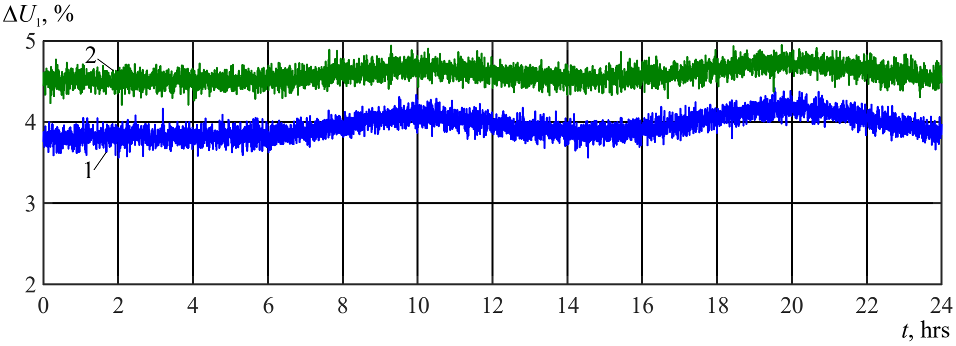

Fig. 9. Daily plots of ΔU_1 change: 1 – basic automatic control system; 2 – designed automatic control system

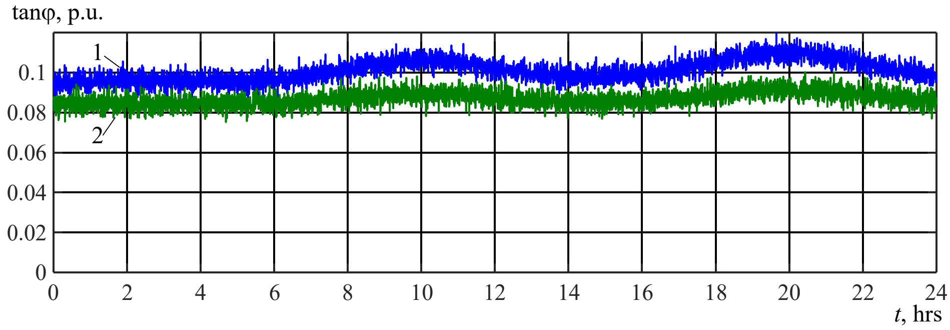

Fig. 10. Plots of $\tan\varphi$ change: 1 – basic automatic control system; 2 – designed automatic control system

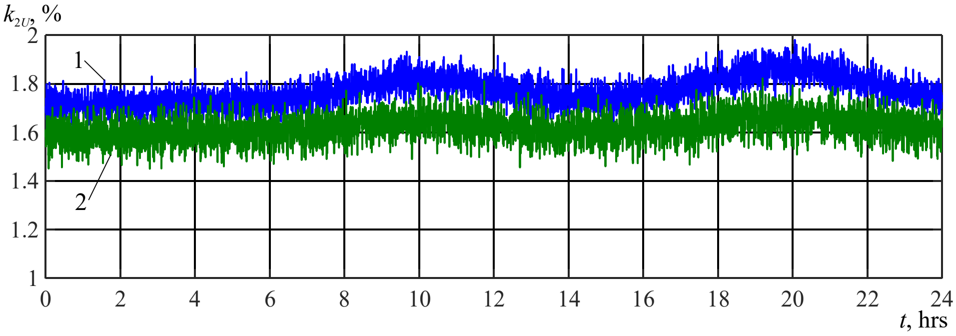

Fig. 11. Plots of k_{2U} change: 1 – basic automatic control system; 2 – designed automatic control system

Analysis of the plots shown in Fig. 9, 10 revealed that for the basic ACS system, the value of the steady-state voltage deviation ΔU_1 is in the range of 3.56...4.42%. With such control, a significant margin of ΔU_1 is observed up to the permissible limit of 5%. At the same time, a level of reactive power compensation is observed, for which the mathematical expectation $M[\tan\varphi] = 0.101$. Unlike the basic one, the designed ACS system, in the presence of a margin of ΔU_1, reduces the value of the weighting coefficient $w_{\Delta U}$, while increasing the $w_{\tan\varphi}$ and w_{k2U} values. As a result, the ΔU_1 values shift to the range of 4.21...4.95%. At the same time, an increase in the level of reactive power compensation is observed – the mathematical expectation $M[\tan\varphi] = 0.087$, which is 13.9% less than in the basic ACS system.

Table 3

Comparison of energy performance indicators of the ACS system

No. of entry	Indicator	Basic ACS	Designed ACS
1	Mathematical expectation $M[\Delta U_1]$, %	3.95	4.57
2	Integral probability $P[-5\% < \Delta U_1 < 5\%]$, r. u.	1.0	1.0
3	Mathematical expectation $M[k_{2U}]$, %	1.77	1.62
4	Integral probability $P[k_{2U} < 2\%]$, r. u.	1.0	1.0
5	Mathematical expectation $M[\tan\varphi]$	0.101	0.087

Analysis of the plots in Fig. 11 revealed that for the case of the basic ACS, the value of the asymmetry coefficient k_{2U} is in the range of 1.57...1.99%. In this case, there is practically no margin to the limit of the permissible level (2%). Unlike the basic one, the designed ACS provides more effective symmetrization, for which k_{2U} is in the range of 1.45...1.82%. At the same time, for the variant of the designed ACS, the mathematical expectation $M[k_{2U}] = 1.62\%$, which is 8.5% less than for the case of the basic ACS.

6. Discussion of results based on investigating the automatic control system for a symmetry-compensating device

As shown in Fig. 2–4 and in Table 2, the justified composition of the input linguistic variables and the constructed expert rule base allowed us to implement the algorithm for dynamic tuning of ACS. The use of levels of approximation of the current values of the steady-state deviation and voltage asymmetry to their normatively permissible limits ensured the ability of the controller to adaptively adjust the weight coefficients of the objective function. At the same time, the computer simulation model built, the generalized structural diagram of which is shown in Fig. 6, allowed us to integrate the synthesized fuzzy algorithm into the general circuit of the automatic control over SCD. This provided an instrumental basis for verifying the proposed approach to the automatic control over SCD.

Our results of computer simulation indicate the superiority of the designed ACS with a fuzzy algorithm for determining the weight coefficients over existing SCD ACS. According to the data given in Table 3, the main advantages of using the designed ACS are a decrease in the values of mathematical expectations tan$\boldsymbol{\varphi}$ by 13.9% and k_{2U} by 8.5% compared to the basic ACS. The obtained effect is explained by the ability of the ACS to dynamically change the weighting coefficients. According to the plots in Fig. 9–11, during periods of time when there is a margin of ΔU_1 in the network, the fuzzy controller reduces the value of the coefficient $w_{\Delta U}$, increasing the $w_{\tan\boldsymbol{\varphi}}$ and w_{k2U} values. In this way, the regulatory resource of the SCD ACS is redistributed towards increasing the level of reactive power compensation and reducing voltage asymmetry. Such an effect cannot be achieved when using the basic ACS with weighting coefficients that do not change over time.

It is worth noting that the increase in the value of the mathematical expectation $M[\Delta U_1]$ from 3.95% to 4.62% does not cause violations of the regulatory requirements for the quality of electricity.

Unlike the ACS described in [11], in the designed ACS, the deviation and voltage asymmetry margins relative to the permissible limits (ΔU_{margin}, $k_{2Umargin}$) are used as input variables of the fuzzy controller. Due to this, the weighting coefficients of the designed ACS adaptively change depending on the current values of the parameters of the distribution network mode. As a result, the use of the designed ACS makes it possible to achieve a positive effect in time intervals when the current values of one or more optimization criteria (Fig. 9) are within the permissible range with a certain margin.

It should be noted that the efficiency of the designed ACS significantly depends on the ΔU_{margin} and $k_{2Umargin}$ values of margins. In the case when the operating parameters of the distribution network are close to the permissible values for a long time, the fuzzy controller will provide the maximum value of the weight coefficient $w_{\Delta U}$. In this case, the characteristics of the designed ACS will approach the basic ACS with weight coefficients that do not change over time. Therefore, it is most advisable to use the designed SCD ACS in distribution electrical networks with a high level of throughput.

The designed ACS can be implemented on the basis of modern industrial microcontrollers of the ARM Cortex-M architecture. The software implementation of the algorithm for adaptive determination of weight coefficients can be implemented by automatically generating C/C++ code from the constructed Simulink model using the MATLAB Coder/Simulink Coder tools.

A significant limitation for the technical implementation of the designed ACS is the need to use high-speed switching equipment for phase-by-phase change in the values of capacitive resistances. In addition, the existence of a system for monitoring the parameters of the distribution network mode in real time is mandatory for the designed ACS.

The disadvantage of the designed ACS is the need for expert tuning of the base of 27 rules. This can be a rather laborious process for complex cases of distribution network configurations. To automate the process of tuning the ACS parameters, the use of adaptive neuro-fuzzy networks and evolutionary optimization methods seems promising. In addition, it is promising to study the use of multi-agent control systems to coordinate the joint operation of several SCDs.

7. Conclusions

1. The results of our research substantiated the choice of input variables of the fuzzy controller for the optimal ACS system. As these input variables, the value of the load factor and the value of the reserves for the deviation and asymmetry of the voltage relative to the permissible limits were selected. The constructed rule base allowed us to synthesize a fuzzy controller that provides an adaptive change in the weight coefficients for the optimal SCD ACS.

2. As a result of the construction of a computer simulation model of SCD ACS, with an integrated fuzzy controller module for adaptive change in the weight coefficients, it was established that the model is operational. The computer model built makes it possible to study the operating modes of the distribution electric network with a sharply changing load and SCD.

3. The results of computer simulation confirmed a significantly higher efficiency of the proposed adaptive ACS compared to the basic one. It is established that the application of the designed ACS enables a reduction in the mathematical expectations of the reactive power factor $M[\tan\boldsymbol{\varphi}]$ by 13.9% and the unbalance factor $M[k_{2U}]$ by 8.5%. At the same time, the compliance of values of the steady-state voltage deviation and voltage unbalance in the reverse sequence with the regulatory requirements is ensured.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Petro Plieshkov: Conceptualization, Methodology, Writing – original draft; **Vasyl Zinzura:** Methodology, Software; **Kateryna Petrova:** Software, (Data curation, Writing – original draft; **Valentyn Soldatenko:** Conceptualization, Formal Analysis, Writing – review & editing; **Andrii Nekrasov:** Formal Analysis, Writing – review & editing.

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