Розглянуто конфігурацію та принцип роботи статичного тиристорного компенсатора реактивної потужності з примусовою комутацією та вольтододаванням для мереж з компенсованою нейтраллю. Визначено інтегральні показники енергетичного процесу компенсатора у випадку його живлення напругою прямокутної форми у разі незалежного керування комутуючими тиристорами. При певних значеннях кутів керування тиристорами питомі втрати активної потужності стають меншими за однойменні питомі втрати у разі живлення компенсатора синусоїдною напругою. Це забезпечує його конкурентоздатність по відношенню до інших статичних компенсаторів.

Запропоновано метод багатокоординатного керування статичними тиристорними компенсаторами з примусовою комутацією. Його суть полягає у незалежному керуванні всіма комутуючими тиристорами компенсатора відповідно до цільової функції системи, яка визначається за умови, що питомі втрати активної потужності не перевищують їх економічно обґрунтованого рівня.

Запропоновано схему керування статичним тиристорним компенсатором з примусовою комутацією та вольтододаванням. Застосування схеми дає можливість зменшити втрати активної потужності в компенсаторі під час регулювання реактивної потужності та здійснити незалежне керування фазними реакторами. Мікропроцесорне керування в реальному часі всіма елементами системи дозволяє забезпечити необхідний алгоритм перемикання комутуючих тиристорів та реалізувати багатокоординатне керування енергетичними процесами компенсатора. Розроблено алгоритм роботи мікропроцесорної системи статичного компенсатора під час регулювання реактивної потужності. Цей алгоритм за рахунок збільшення коефіцієнта вольтододавання під час дії негативної півхвилі напруги живлення дозволяє зменшити питомі втрати активної потужності в електричній мережі та компенсаторі

Ключові слова: статичні тиристорні компенсатори, примусова комутація, реактивна потужність, багатокоординатне керування, вольтододавання

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CONSTRUCTING A METHOD OF MULTI-COORDINATE CONTROL OVER THE STATIC THYRISTOR COMPENSATORS WITH FORCED COMMUTATION

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1. Introduction

The industrial production of recent years has been accompanied by an ever-increasing consumption of reactive power, as compared with the active power, and the growing share of sharply variable loads, which is why the issue of reactive power compensation is of special importance. Static thyristor compensators (STCs) that act as a source of reactive power is an effective tool for resolving the tasks of transmitting and distributing electrical energy, associated with the large and rapid fluctuations in the reactive power. Most power reactive sources are characterized by the dependence of active power specific losses on the mode of operation [1].

The sharply variable loads are characterized by the asymmetry of power consumption in the phases of supply voltage, as well as the surges in reactive power. Voltage fluctuations that occur in this case adversely affect consumers and increase the losses of electrical energy. It is possible to ensure the permissible level of voltage fluctuations and to reduce the losses of electrical energy through the rapid phase-to-phase reactive power compensation.

To improve the efficiency of using STC as a source of reactive power, it is necessary to reduce the losses of active power in it and in the network, to ensure independent control over the opening and closing angles of its commutation thyristors. In addition, it is required to refine a mathematical model of STC as a system with the variable parameters and structure, as well as to develop the systems of multi-coordinate reactive power control. Therefore, these fields of research into static compensators are important for the development of electricity generation and are relevant.

2. Literature review and problem statement

The electric equipment exposed to sharply variable loads exhibits, in addition to the high consumption of reactive power and the generation of the higher harmonic currents, the non-symmetry of power consumption in the phases of power voltage, as well as the significant surges in reactive power [2]. In this case, the power grid experiences voltage fluctuations [3], which adversely affect consumers of electrical energy. It is possible to ensure, under these conditions, the permissible level of voltage fluctuations for powerful electrical equipment through the rapid compensation of reactive power with the help of static thyristor compensators. By using power thyristors, STCs are capable of switching a load of high power at proper performance speed [4]. A promising tool for resolving this issue is to use the STCs of reactive power with forced commutation.

The static thyristor compensators with forced commutation employ a direct or indirect compensation of reactive power.

The STCs with a direct compensation of the reactive power require specialized fast thyristors with a short-time recovery of shut-off properties; they have a complicated circuit configuration, low reliability, a small overvoltage margin [5, 6], and a poor overload capacity [7–9]. Currently, compensators with a direct compensation of reactive power are fabricated based on a voltage converter with the forced commutation, which use, as power switching devices, the bipolar transistors with an insulated shutter or two-operating thyristors [10]. Control over reactive power is carried out by changing the amplitude of output voltage at the expense of pulse-width modulation.

A promising direction in the development of STCs with direct compensation is the use of STATCOM as an independent device or a base element for other devices. Paper [11] reports the results of examining the STATCOM circuit, containing two bridge voltage inverters, the same phases of which are connected to the opposite clamps of the secondary winding of the transformer. The primary windings of this transformer are connected to a three-phase electrical network. It is shown that this circuit, due to the pulse-width modulation, ensures high-quality spatial vector control over the voltage and active power in an electric network. However, the unresolved issue is the reduction of active power losses, since the application of the pulse-width modulation algorithms with a frequency much greater than the frequency of the network leads to the increased active losses in the valve part of the compensator.

The reactive power compensator with an induction energy storage unit [12] employs a three-phase bridge converter is used with the inductance on the DC side and the D-shaped *LC* low-frequency filter on the AC side. Reactive power is controlled in it by changing the opening angle of the transistors relative to the network voltage. This compensator has a step-less adjustment of reactive power, is insensitive to the voltage higher harmonics and is simpler structurally compared to the STATCOM-type systems.

The disadvantages of the compensator with an inductive energy storage unit include:

1) the narrow adjustment range of the opening angle of transistors, which is about half the electrical degree;

2) the impossibility to adjust power down from rated;

3) high specific losses of active power during reactive power adjustment.

Three schemes of power circuits of hybrid static compensators were proposed in work [13]. All of them include the thyristor-controlled reactors and differ in the configuration of active filters. In the scheme with a passive *LC* filter with a sequential active filter, the additional active losses to install the active filter is 1.4 % of the power of a three-phase load. The scheme with a phase conduction capacitor with a consistent active filter differs from the previous one by greater losses constituting 4 % of the power of a three-phase load. The least energetically efficient scheme employs a parallelly-enabled static synchronous compensator. The active losses in it reach 80 % of the power of a three-phase load. An analysis of the above circuits reveals that they do not solve the issue of reducing the active losses when controlling reactive power and do not ensure the multi-coordinate control over static compensators.

The hybrid compensation of reactive power was examined in paper [14]. It is implemented through a stepped-managed shunt reactor. The compensator is composed of the high-ohm transformers, consistently connected reactors, mechanical switches, and thyristors. Reactors are consistently connected to the linear secondary winding. The available number of successive reactors changes by thyristors and mechanical breakers to adjust the power. Rapid control over the power of the reactor with a controlled shunt is provided by thyristors, while mechanical switches are used to bypass them during operation without drastic changes in reactive power to simplify the cooling system of the thyristors. Using this scheme does not reduce active losses in the compensator during the adjustment of reactive power and ensure independent control over the opening and closing angles of the commutation thyristors.

Study [15] considered an industrial controller specifically designed for two-and three-level converters, which is adapted for the use on the asymmetric nine-level active power filter. An important advantage of this controller is the low-frequency switching of the nine-level converter. Given this, the active losses during switching were reduced. At the same time, the unresolved issue is the possibility of reducing the active losses in the compensator when controlling the reactive power.

The indirect compensation of reactive power can be implemented on the base of thyristor controllers of variable voltage with forced commutation [16], which enable the time-steady commutation capability and the independence of the switching node parameters on the load parameters. Using the forced commutation makes it possible to improve the energy performance of thyristor controllers of variable voltage and obtain various shapes of voltage on the load. Increasing the frequency of thyristor switching makes it possible to remove the shift of the basic harmonic of the network current during regulation and to reduce the mass and dimensions of filters. However, these schemes have two drawbacks. The synchronous switching of phase reactors decreases performance speed as the steady mode of operation is achieved not over a single but over several periods of power supply voltage, and there is no possibility of independent phase control over the reactive capacity of the static compensator.

Our analysis of special features in the operation of the examined static compensators indicates the need to design controllers with forced commutation and phased control over reactive power at small losses of the active power in them. Since the reactive power control is executed mainly by changing the opening angles of commutation thyristors, it is necessary to improve a method of independent control over the opening and closing angles of the commutation thyristors in STC with the forced commutation. Little attention has been paid to the techniques of multi-coordinate control over reactive power in the static compensators with forced commutation.

3. The aim and objectives of the study

The aim of this study is to optimize the operational modes of the static thyristor compensators with forced commutation and to improve the techniques for the multi-coordinate phased control over reactive power in order to improve the efficiency of using the static compensators.

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

– to build a mathematical model of STC with the forced commutation and voltage addition and to investigate the energy processes in it in order to ensure the possibility of reducing the active power losses when controlling the reactive power;

– to construct a method for the multi-coordinate control over STC with the forced commutation and voltage addition, using which the switching of power thyristors is carried out depending on the system objective function;

– to improve the scheme of phased control over the reactive power in STC with the forced commutation and voltage addition and to devise a flowchart of the operation algorithm of its controlling microcontroller in order to ensure the optimization of the compensator operation modes.

4. A mathematical model of STC with the forced commutation and voltage addition

The bipolar voltage addition is used for the cases where it is necessary to control the STC output voltage relative to the rated voltage. In this case, it is necessary that, during the use of voltage addition, the reactive power should increase while the specific loss of active power should decrease [17]. This is only possible when using a specific algorithm for applying the voltage addition. A scheme of the static controller over reactive power [18], which implements this algorithm, is shown in Fig. 1.

The reactive power static controller operates in the following way. When the power voltage is supplied, the *C*1–*C*9 capacitors are charged from the secondary windings *w*2 and *w*3 in transformer *T* through the single-phase bridge rectifiers *VD*1–*VD*9 at the polarity indicated in Fig. 1 without parentheses. When exposed to a positive half-wave of the supply voltage, the opening of thyristor *VS*1 enables the equipotentiality of points *a*1 and neutral *N* of the transformer; the phase reactor *LR*1 is fed with voltage. The capacitor *C*1 is recharged via the thyristor *VS*1 and the winding of throttle *L*1, acquiring the polarity indicated in Fig. 1 in parentheses. To close the *VS*1 thyristor, the thyristor *VS*3 opens and the capacitor *C*3 is recharged via the thyristor *VS*3 and the winding of the throttle *L*3. The winding of the throttle *L*3 is induced with an electromotive force under which the thyristor *VS*1 closes. When one opens the *VS*3 thyristor, there is the equipotentiality of points *a*3 and the neutral *N* of the transformer; the phase reactor *LR*1 would be closed through the rectifier *VD*3, thereby providing for the current continuity for the case of an active-inductive load. To close the *VS*3 thyristor, one opens the thyristor *VS*2. In this case, there is the equipotentiality of points *a*2 and the neutral *N* of the transformer; the *LR*1 phase reactor is given a negative half-wave of the supply voltage. The capacitor *C*2 is recharged via the thyristor *VS*2 and the throttle *L*2 winding, acquiring the polarity indicated in Fig. 1 in parentheses. To close the *VS*2 thyristor, one opens the thyristor *VS*3 and the capacitor *C*3 is recharged via the thyristor *VS*3 and the winding of the throttle *L*3. This winding is induced with an electromotive force, under the action of which the thyristor *VS*2 closes.

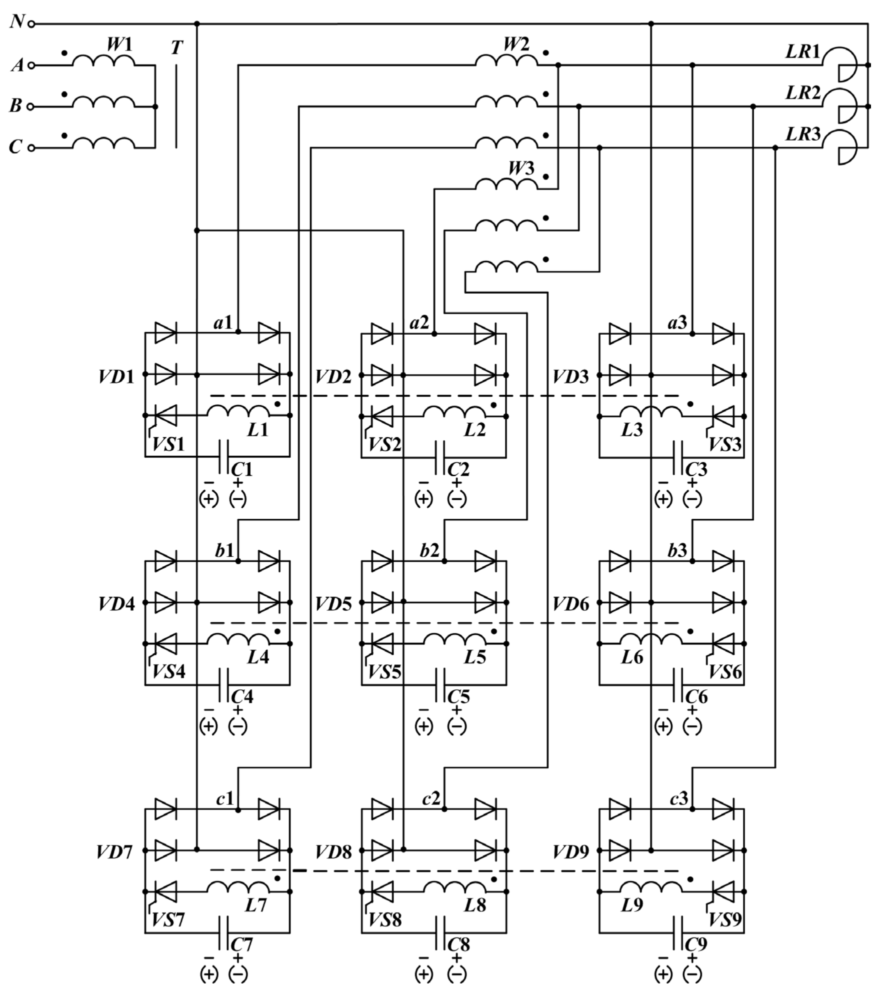

Fig. 1. A circuit of the static controller of reactive power

The processes that occur in phases *b* and *c* of the static controller of reactive power during switching the thyristors *VS*4, *VS*5, *VS*6 and *VS*7, *VS*8, *VS*9 proceed similarly and independently. The positive half-wave of the supply voltage is determined by the output voltage of the secondary winding of the transformer *w*2, and the negative half-wave – by the output voltage of the secondary winding of the transformer *w*3. Under the action of the positive half-wave of the supply voltage the static controller is a consumer of active power, and in the case of the negative half-wave of the supply voltage – a generator of active power. In this case, due to the voltage addition when changing the angles of control over the commutation thyristors, it is possible to reduce the losses of active power. At the same time, the reactive power would increase while the steepness of the adjusting characteristic of the controller – increase.

In accordance with the operation algorithm of an STC with the forced commutation, under the action of a bipolar supply voltage, the first to open is the first commutation thyristor, followed by the second commutation thyristor that closes the first one. For all existing techniques to adjust the reactive power, the angles of opening and closing these thyristors depend on the angle of control of the first commutation thyristor. Thus, such regulation of the reactive power is carried out by means of only one coordinate – control angle and, therefore, does not make it possible to solve the optimization problems for an STC with the forced commutation effectively.

A unique feature of the STC with forced commutation is the possibility of independent control over the opening and closing angles of commutation thyristors. The purpose of this control can be characterized by a certain objective function, which would depend on the scalar set of control angles of the commutation thyristors. The objective function can be derived on the basis, for example, of the necessity to ensure the reduced specific losses of active power when controlling the reactive power of STC or its proper performance speed for the compensation of fast-changing reactive loads. Control over reactive power depending on the objective function is the multicoordinate control over an STC with the forced commutation as the control process is carried out through an independent change in all angles of control over the commutation thyristors.

Theoretically, the considered STCs with the forced commutation can produce four independent angles of control over the commutation thyristors: α_1, α_2, α_3 and α_4. Moreover, the α_1 and α_3 angles are the angles of opening the first commutation thyristor, respectively, under the action of the positive and negative half-wave of the supply voltage, and the α_2 and α_4 angles are the angles of opening the second commutation thyristor and, accordingly, closing the first commutation thyristor. Practically, only the α_1, α_2 and α_3 control angles are independent. The control angle α_4 should be determined by the moment when the phase reactor current passes through zero. In this case, a quasi-established mode of the power circuit occurs over a single period of the supply voltage. Otherwise, the current through the phase reactor would be different from zero, and over the next half-period of the supply voltage during the opening of the first commutation thyristor, the initial conditions for the current would not be zero. That would lead to the disruption of the quasi-established mode of the compensator power circle.

The electromagnetic processes in the power circuit of an STC with the forced commutation for networks with a compensated neutral in the presence of voltage addition are described by the generalized differential equation of the first order:

$$x_{|2-n|}\frac{di_n(\theta)}{d\theta}+r_{|2-n|}i_n(\theta)=(2-n)\nu^{\frac{n-1}{2}}U_m, \qquad (1)$$

where n=1, 2, 3 is the number of the plot at the time diagram of voltage and current; U_m is the amplitude value of a rectangular voltage; ν is the voltage addition coefficient. The equation (1) holds for all control techniques of STC with the forced commutation.

The shapes of control voltages U_{C1}, U_{C2} (Fig. 2, *a*, *b*), the supply voltage and the current through the load (Fig. 2, *c*) in an STC with the forced commutation for networks with a compensated neutral in the presence of voltage addition in the case of independent control over the commutation thyristors. In the first section $\alpha_1\le\theta\le\pi-\alpha_2$, the total active-inductive resistance of the secondary winding of the transformer and phase reactor is fed with voltage U_m. In the second section $\pi-\alpha_2\le\theta\le\pi+\alpha_3$, there is no voltage. In the third section $\pi+\alpha_3\le\theta\le\theta_O$, the total active-inductive resistance of the secondary winding of the transformer and phase reactor is fed with voltage $-\nu U_m$.

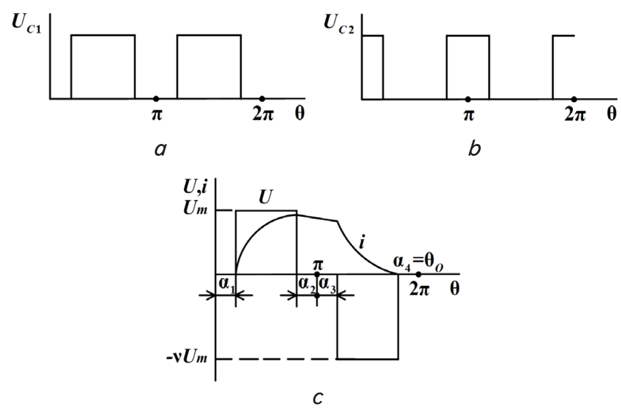

Fig. 2. Time diagrams of STC with forced commutation and voltage addition for the case of independent control over commutation thyristors: *a* – the shape of control voltage U_{C1}; *b* – the shape of control voltage U_{C2}; *c* – the shape of supply voltage and current through load

Based on equation (1) and the corresponding initial conditions, the currents in the first, second, and third plots of the time diagram (Fig. 2) will take the form:

$$i_1(\theta)=\frac{I_m}{\rho_1}\left[1-e^{\rho_1(\alpha_1-\theta)}\right], \qquad (2)$$

$$i_2(\theta)=\frac{I_m}{\rho_1}\left[1-e^{\rho_1(\alpha_1+\alpha_2-\pi)}\right]\cdot e^{\rho_0(\pi-\alpha_2-\theta)}, \qquad (3)$$

$$i_3(\theta)=-\frac{\nu I_m}{\rho_1}+\frac{I_m}{\rho_1}\begin{bmatrix}\nu+\left(1-e^{\rho_1(\alpha_1+\alpha_2-\pi)}\right)\times\\ \times e^{-\rho_0(\alpha_2+\alpha_3)}\end{bmatrix}\cdot e^{\rho_1(\pi+\alpha_3-\theta)}. \qquad (4)$$

Equating expression (4) to zero, we obtain the angle of closing the commutation thyristor:

$$\theta_B = \pi + \alpha_3 + \frac{1}{\rho_1}\ln\frac{\nu + \left(1 - e^{\rho_1(\alpha_1+\alpha_2-\pi)}\right)\cdot e^{-\rho_0(\alpha_2+\alpha_3)}}{\nu}. \quad (5)$$

Considering expressions (2), (4), and (5), the reactive power and losses of active power constitute, in relative units:

$$Q^*(\alpha_1,\alpha_2,\alpha_3) = -\frac{1}{\pi}\left[-\frac{1}{\rho_1}\int_{\alpha_1}^{\pi-\alpha_2} i_{*1}(\theta)\delta(\theta-\pi+\alpha_2)d\theta - \frac{\nu}{\rho_1}\int_{\pi+\alpha_3}^{\theta_Q} i_{*3}(\theta)\delta(\theta-\pi-\alpha_3)d\theta\right] = \frac{1}{\rho_1\pi}\left[1 - e^{\rho_1(\alpha_1+\alpha_2-\pi)} + \nu\left(1-e^{\rho_1(\alpha_1+\alpha_2-\pi)}\right)\cdot e^{-\rho_0(\alpha_2+\alpha_3)}\right], \quad (6)$$

$$\Delta P^*(\alpha_1,\alpha_2,\alpha_3) = \frac{1}{\pi}\left[\begin{array}{l}\frac{1}{\rho_1}\int_{\alpha_1}^{\pi-\alpha_2} i_{*1}(\theta)u_*(\theta)d\theta + \\ +\frac{1}{\rho_1}\int_{\pi+\alpha_3}^{\theta_Q} i_{*3}(\theta)u_*(\theta)d\theta\end{array}\right] = \frac{1}{\rho_1\pi}\left[\begin{array}{l}\pi-\alpha_1-\alpha_2+ \\ +\frac{\nu^2}{\rho_1}\ln\frac{\nu+\left(1-e^{\rho_1(\alpha_1+\alpha_2-\pi)}\right)\cdot e^{-\rho_0(\alpha_2+\alpha_3)}}{\nu}+ \\ +\frac{1}{\rho_1}e^{\rho_1(\alpha_1+\alpha_2-\pi)}-\frac{1}{\rho_1}- \\ -\frac{\nu}{\rho_1}\left(1-e^{\rho_1(\alpha_1+\alpha_2-\pi)}\right)\cdot e^{-\rho_0(\alpha_2+\alpha_3)}\end{array}\right], \quad (7)$$

where

$$i_{*1}(\theta) = \frac{i_1(\theta)}{I_m},\quad i_{*3}(\theta) = \frac{i_3(\theta)}{I_m},\quad u_*(\theta) = \frac{u(\theta)}{U_m}$$

are, accordingly, the currents and voltage in relative units; $\delta(\theta-\pi+\alpha_2)$, $\delta(\theta-\pi-\alpha_3)$ are the offset Dirac delta functions.

It follows from expressions (6) and (7) that the integrated indicators of the energy process $Q^*(\alpha_1,\alpha_2,\alpha_3)$ and $\Delta P^*(\alpha_1,\alpha_2,\alpha_3)$ are functions of the scalar set of control angles α_1, α_2, α_3. Therefore, by using these indicators, it is possible to estimate the effectiveness of energy processes in an STC with the forced commutation for any techniques of their control.

5. A method of multicoordinate control over an STC with the forced commutation and voltage addition

To improve the efficiency of an STC with the forced commutation as the source of reactive power, it is necessary that the specific losses of active power in it should not exceed the level of the basic variant when the static compensator is powered by a sinusoid voltage:

$$\Delta P_Q(\alpha_1,\alpha_2,\alpha_3) = \frac{\Delta P^*(\alpha_1,\alpha_2,\alpha_3)}{Q^*(\alpha_1,\alpha_2,\alpha_3)} \le \rho_1, \quad (8)$$

where ρ_1 is the resistivity of the power circuit of the compensator. By denoting $\alpha_1+\alpha_2 = x$ and $\alpha_2+\alpha_3 = y$ according to expressions (6)–(8), we obtain the objective control function of an STC with the forced commutation for networks with a compensated neutral in the presence of voltage addition:

$$z(x,y) = \frac{\rho_1(\pi-x)+\nu^2\ln\frac{\nu+\left(1-e^{\rho_1(x-\pi)}\right)\cdot e^{-\rho_0 y}}{\nu}}{\rho_1\left(1-e^{\rho_1(x-\pi)}\right)\left(1+\nu e^{-\rho_0 y}\right)} - \frac{1}{\rho_1} - \rho_1. \quad (9)$$

The objective control function of an STC with the forced commutation should not be larger than 0: $z(x,y)\le 0$. The objective control functions and the boundaries of their transition to the region of negative values for an STC with the forced commutation for networks with a compensated neutral in the presence of voltage addition for values $\nu = 1.6; 1.9; 2.2$ are shown in Fig. 3, 4, respectively.

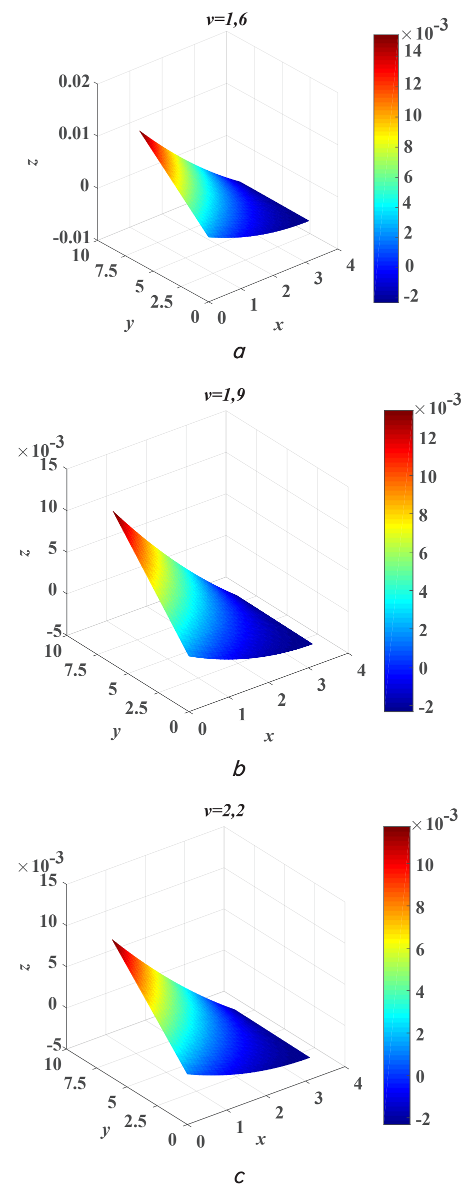

Fig. 3. The objective control functions of an STC with the forced commutation and voltage addition: *a* – for value ν=1.6; *b* – for value ν=1.9; *c* – for value ν=2.2

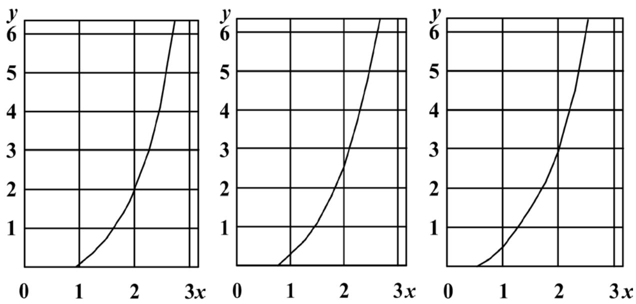

Fig. 4. The boundaries of transition of the objective control functions of an STC with the forced commutation and voltage addition to the region of negative values: *a* – for value ν=1.6; *b* – for value ν=1.9; *c* – for value ν=2.2

The expression for curves that determine the boundaries of the transition of the objective control functions to the region of negative values and the boundary control surfaces for different coefficients of voltage addition for STC are given, respectively, in Tables 1, 2.

Table 1

Dependence of the boundary of the transition of the objective control function to the region of negative values on the voltage addition coefficient

Voltage addition coefficient ν	Boundary of the transition of the objective control function to the region of negative values y	Standard deviation
1.6	$-11.4+34.5x-43.1x^2+$ $+27.4x^3-8.61x^4+1.09x^5$	0.0241
1.9	$-8.28+27.05x-35.95x^2+$ $+24.55x^3-8.2x^4+1.1x^5$	0.0182
2.2	$-5.15+19.6x-28.8x^2+$ $+21.7x^3-7.79x^4+1.11x^5$	0.012

Table 2

Dependence of the boundary control surface on the voltage addition coefficient

Voltage addition coefficient ν	Boundary control surface α_{3lim}
1.6	$-\alpha_{2lim}-11.4+34.5(\alpha_{1lim}+\alpha_{2lim})-$ $-43.1(\alpha_{1lim}+\alpha_{2lim})^2+27.4(\alpha_{1lim}+\alpha_{2lim})^3-$ $-8.61(\alpha_{1lim}+\alpha_{2lim})^4+1.09(\alpha_{1lim}+\alpha_{2lim})^5$
1.9	$-\alpha_{2lim}-8.28+27.05(\alpha_{1lim}+\alpha_{2lim})-$ $-35.95(\alpha_{1lim}+\alpha_{2lim})^2+24.55(\alpha_{1lim}+\alpha_{2lim})^3-$ $-8.2(\alpha_{1lim}+\alpha_{2lim})^4+1.1(\alpha_{1lim}+\alpha_{2lim})^5$
2.2	$-\alpha_{2lim}-5.15+19.6(\alpha_{1lim}+\alpha_{2lim})-$ $-28.8(\alpha_{1lim}+\alpha_{2lim})^2+21.7(\alpha_{1lim}+\alpha_{2lim})^3-$ $-7.79(\alpha_{1lim}+\alpha_{2lim})^4+1.11(\alpha_{1lim}+\alpha_{2lim})^5$

An analysis of Fig. 3, 4 reveals that when the voltage addition coefficient ν increases the objective control function $z(x, y)$ moves down, and its transition to the region of negative values occurs earlier. In this case, the region of the negative values of the objective function increases, which makes it possible to reduce the specific losses of active power in an STC with the forced commutation in the presence of voltage addition and to implement the effective technologies of phased control.

Fig. 5 shows the boundary surface controls for different values of the voltage addition coefficient ν: 1.6; 1.9; 2.2.

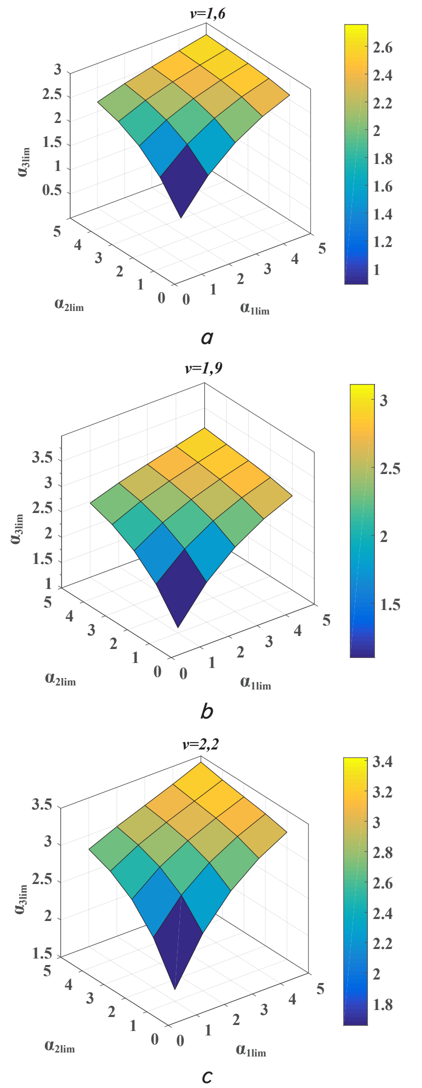

Fig. 5. Boundary control surfaces for different values of the voltage addition coefficient: *a* – for value ν=1.6; *b* – for value ν=1.9; *c* – for value ν=2.2

If the control angle α_3 is located below the boundary surface, then, when controlling the reactive power, the specific losses of active power by STC would be reduced compared to the basic variant. Moreover, the further this angle is from the boundary control surface, the less the specific losses of active power. When the coefficient of voltage addition ν increases, the boundary control surfaces are shifted upwards, which makes it possible to increase the adjustment range of the control angle α_3.

The multi-coordinate control method makes it possible to choose the angle α_3 with such a margin that would ensure when executing the phased control over reactive power, a decrease in the specific losses of active power in the STC. One can also employ a change in the α_1 and α_2 angles to resolve other local tasks.

6. Developing a control circuit and a flowchart of the algorithm to operate the controlling microcontroller of an STC with the forced commutation and voltage addition

The static controller of reactive power, which is included in an STC with the forced commutation in the presence of voltage addition, makes it possible to reduce the specific losses of active power by the compensator by increasing the coefficient of voltage addition ν [19].

These conclusions were drawn for those techniques to control the reactive power of a static compensator, which are partial cases of a multicoordinate control method. Applying the multi-coordinate control method to the static thyristor compensator with the forced commutation in the presence of voltage additions makes it possible to expand its functionality through the emergence of an additional control channel – the voltage addition channel.

Multi-coordinate control over a static thyristor compensator with the forced switching for networks with a compensated neutral in the presence of voltage additions can be ensured by using the control circuit, which is shown in Fig. 6.

The static compensator control circuit includes a microprocessor system. It is composed of microprocessor *MP*, RAM storage device *RAM SD*, permanent storage device *PSD*, terminal *T*, address bus *AB*, data bus *DB*, command bus *CB*. The conjugating devices *CD*1, *CD*2, *CD*3, *CD*4, *CD*5, *CD*6, digital-analog converters *DAC*1, *DAC*2, *DAC*3, and analog-digital converters *ADC*1, *ADC*2 enable processing the signals from sensors and the generation of control signals. The structure of the device circuit, which enables the synchronization and execution of the required algorithm for switching the commutation thyristors, includes: voltage transformer *T*2, voltage sensors *VSD*1, *VSD*2, single-phase bridge rectifiers *VD*1, *VD*2, *VD*3. In addition, the device is equipped with the generators of saw-like voltage *GSLV*1, *GSLV*2 and rectangular uni-polar voltage *GRUPV*, zero-organs *ZO*1, *ZO*2, *ZO*3, *ZO*4, logical elements "OR", "BAN", cycle D-trigger, and pulse generators *PG*1, *PG*2, *PG*3.

The flowchart of the operation algorithm for the controlling microcontroller of an STC with the forced commutation when controlling reactive power is shown in Fig. 7.

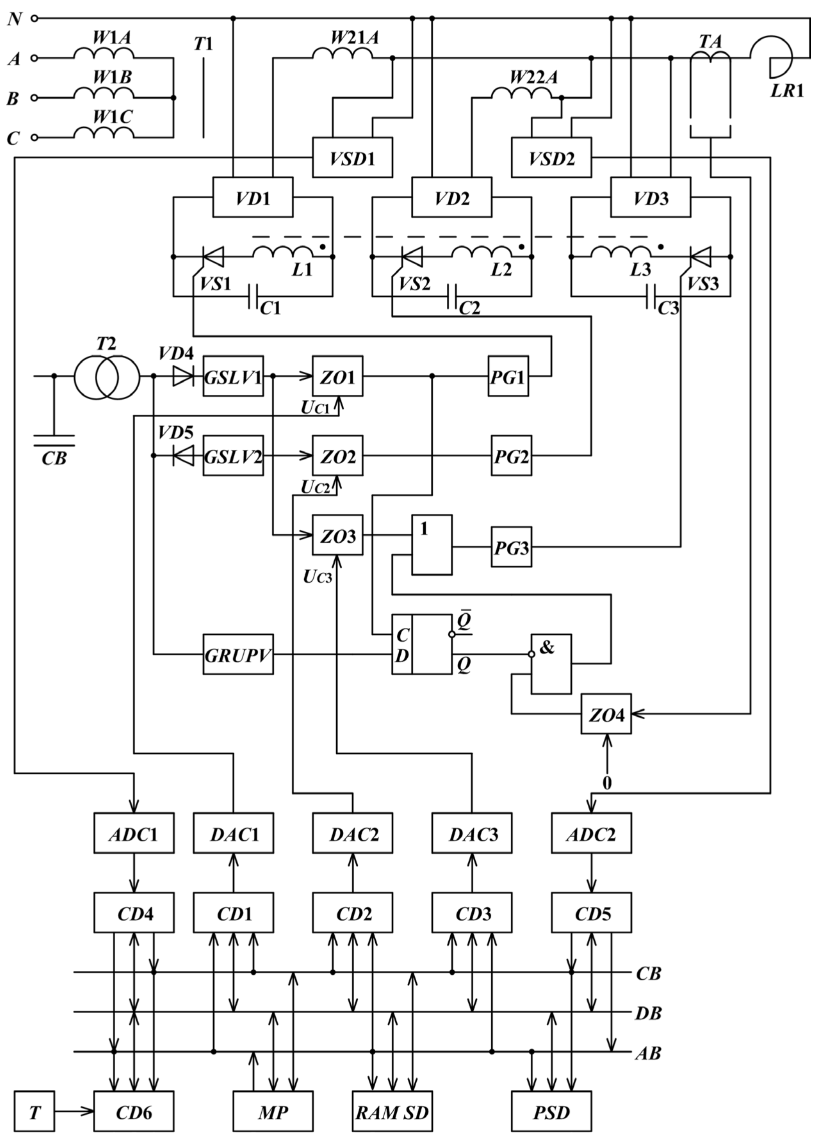

Fig. 6. The control circuit of a static thyristor compensator of reactive power with the forced commutation for networks with a compensated neutral in the presence of voltage addition

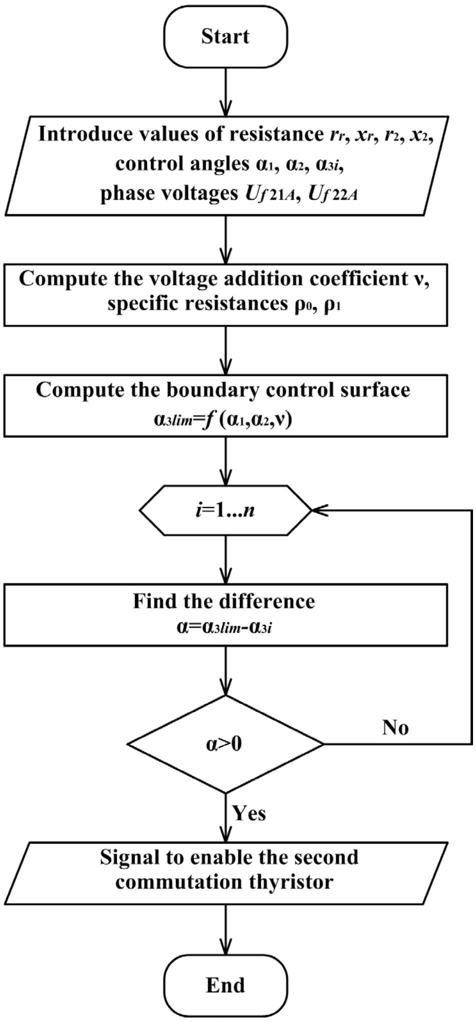

Fig. 7. The flowchart of the operation algorithm for the controlling microcontroller of an STC with the forced commutation for networks with a compensated neutral in the presence of voltage addition when controlling reactive power

The terminal T is used to enter, to the microcontroller, the static compensator's configuration parameters, that is, the values of resistances of the phase reactors and the secondary winding of the transformer $T1$ r_r, x_r, r_2, x_2. One also enters the values of control angles of the commutation thyristors α_1, α_2 and the discrete set of control angles α_{3i}, which, when the index i increases from 1 to n, decreases from π to 0. In addition, the microcontroller receives the values of phase voltages U_{f21A}, U_{f22A} from two split windings w_{21A} and w_{22A} from the voltage sensors $VSD1$, $VSD2$. The phase voltages are found by means of $DAVUL$ on two split windings from the low voltage side.

The microcontroller calculates the coefficient of voltage addition ν, specific resistances ρ_0, ρ_1, the boundary control surface

$$\alpha_{3lim} = f\left(\alpha_{1lim}, \alpha_{2lim}, \nu\right)$$

and the difference $\alpha = \alpha_{3lim} - \alpha_{3i}$. If the condition $\alpha > 0$ is not met, the i index increases by unity, and the difference $\alpha = \alpha_{3lim} - \alpha_{3i}$ is calculated again. This process continues until the condition $\alpha > 0$ is met. Then the microcontroller in the circuit control of an STC with the forced commutation sends a signal to open the second commutation thyristor under the action of a negative half-wave of the supply voltage. By increasing the coefficient of voltage addition ν by using $DAVUL$, it becomes possible to ensure a further reduction of the specific active power losses and an increase in the static compensator performance.

The time diagrams of the operation of individual elements from the control circuit of an STC with the forced commutation for networks with a compensated neutral in the presence of voltage addition are shown in Fig. 8. The transformer $T2$ synchronizes the operation of the logical unit of the control system with power voltage (Fig. 8, *a*). Voltages at the output from rectifiers $VD4$ and $VD5$ (Fig. 8, *b, c*) trigger the generators of saw-like voltage $GSLV1$ and $GSLV2$, respectively, over the odd and even half-periods of the supply voltage. The saw-like voltages generated by $GSLV1$ and $GSLV2$ are compared at the zero-organs $ZO1$, $ZO2$ and $ZO3$ with the control voltages, which are acquired from the outputs $DAC1$, $DAC2$, and $DAC3$ of the microcontroller (Fig. 8, *d–f*). At the time of equality between the saw-like voltages and control voltages at the outputs $ZO1$, $ZO2$ and $ZO3$, the control pulses are generated (Fig. 8, *g–i*). The control pulse from the output of the pulse generator $PG1$ is received by the control electrode of the commutation thyristor $VS1$, thereby opening it. Due to this, the rectangular voltage of the first split secondary winding w_{21A} in the transformer $T1$ is fed to the phase reactor $LR1$ and current is induced in it (Fig. 8, *l*).

To prevent the unwanted opening of thyristor $VS3$ when opening the thyristor $VS1$, the blocking of the pulse is implied, which is formed at this time at the output $ZO4$. This is accomplished by a cyclic D-trigger with potential control and a key built on the "BAN" logical element. When the pulse from the output of the logical element "OR" arrives at the synchronization input C of the cyclic D-trigger, the signal at its direct output Q would repeat the signal, which is fed to the information input D from $GRUPV$ (Fig. 8, *k, l*). Since in this case, the direct output of the D-trigger produces a logical unity, the key would be open while the pulse from the output $ZO4$ would be blocked.

The commutation thyristor $VS1$ closes after opening the thyristor $VS3$ at the time when its control electrode receives, through the logical element "OR" and the generator $PG3$, the control pulse from $ZO3$ (Fig. 8, *i*), which occurs when comparing the saw-like voltage U_{GSLV1} with the control voltage U_{C3} (Fig. 8, *f*). At this point, the first split secondary winding w_{21A} of the transformer $T1$ opens, and the phase reactor is short-closed, which ensures the current continuity through it. When the pulse from the output of the generator $PG2$ (Fig. 8, *h*) arrives, the thyristor $VS2$ opens while the thyristor $VS3$ closes. Next, the second split secondary winding w_{22A} of the transformer $T1$ is connected to the phase reactor and it is fed with the phase voltage of the opposite polarity, the amplitude of which, due to $DAVUL$, can vary within the established limits. When the current through the phase reactor is reduced to zero, the output $ZO4$ produces a control pulse, which, through the closed key and the logical element "OR", would arrive at the control electrode in the thyristor $VS3$. In this case, the thyristor $VS3$ opens and the thyristor $VS2$ closes.

Thus, the proposed scheme to control an STC with the forced commutation makes it possible to independently control the phase reactors of each phase. In addition, it provides the required algorithm for switching the commutation thyristors and microcontroller control in real-time over all the elements of the system, thereby making it possible to reduce the specific losses of active power in the static compensator and electrical network.

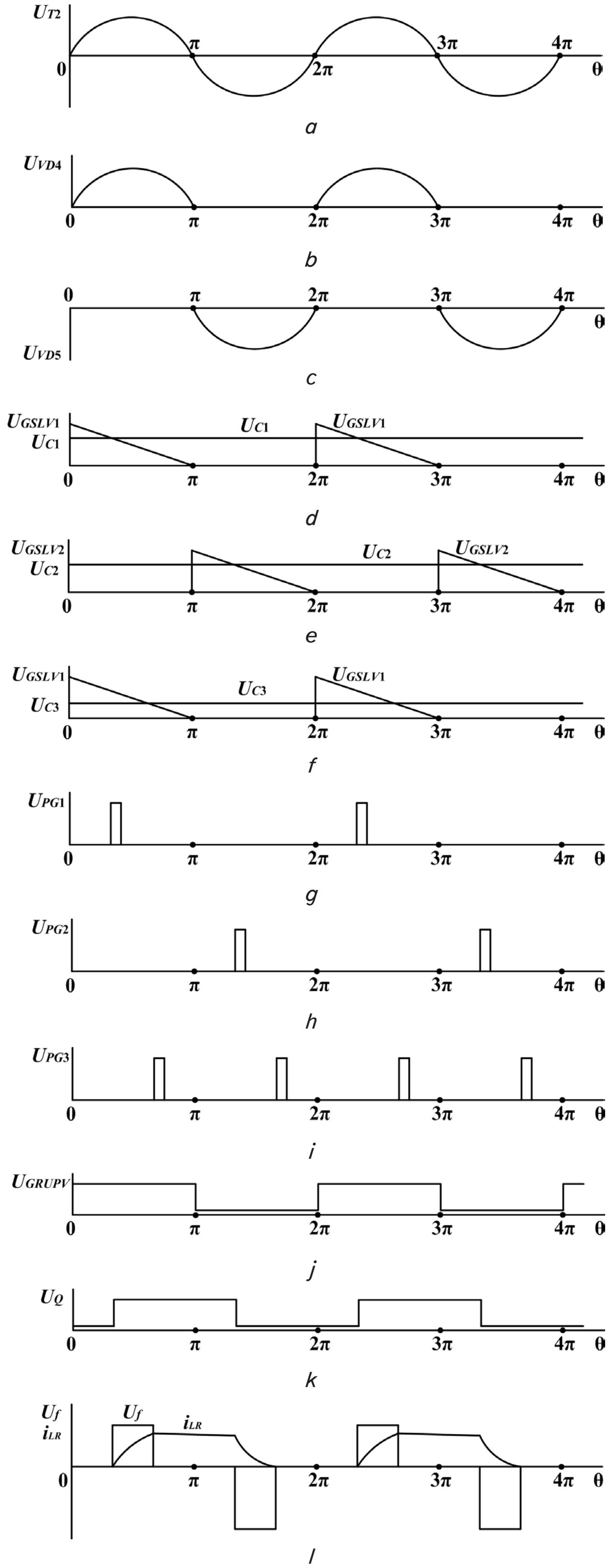

Fig. 8. Time diagrams of the operation of individual elements in the control circuit of an STC with the forced commutation and voltage addition: *a* – the shape of voltage of the transformer *T*2; *b* – the shape of voltage at the output from the rectifier *VD*4; *c* – the shapes of voltage at the output from the rectifier *VD*5; *d* – the saw-like voltage *GSLV*1 compared to the control voltage U_{C1}; *e* – the shape of voltage *GSLV*2 compared with the control voltage U_{C2}; *f* – the saw-like voltage *GSLV*1 compared with the control voltage U_{C3}; *g* – control pulse U_{PG1}; *h* – control pulse U_{PG2}; *i* – control pulse U_{PG3} control; *j* – the signal sent to the information entrance *D* from *GRUPV*; *k* – the signal at the direct output *Q* of the cyclic *D*-trigger; *l* – the shapes of voltage of the first split secondary winding of the transformer *T*1 and the current of the phase reactor *LR*1

7. Discussion of results of studying the mathematical model of an STC with the forced commutation and voltage addition

It is known that when an STC with the forced commutation is powered by a sinusoid voltage the specific losses of active power do not depend on the thyristor opening angle α and remain constant. That does not make it possible to implement the efficient technologies of reactive power control in these static compensators. The use of a rectangular-shape voltage to power an STC with the forced commutation and independent control over the angles of power thyristor switching gives it new features. Therefore, a mathematical model of a given compensator was constructed, which is described by the generalized differential equation of the first order (1). With the help of this equation, I have derived the main energy indicators: the reactive power (6) and the losses of active power (7), which are the functions of control angles of the commutation thyristors α_1, α_2 and α_3.

For the existing methods of regulating reactive power [16], the opening angle of the second commutation thyristor depends on the opening angle of the first commutation thyristor. To overcome this drawback, a method of multi-coordinate control over an STC with the forced commutation and voltage addition was developed. This method implies the following. When the specific losses of active power do not exceed the economically justified level (8), it is possible to build an objective function of the system (9), which depends on the control angles of commutation thyristors α_1, α_2 and α_3. The objective function $z(x, y)$, depending on the value of the voltage addition coefficient ν, determines some control surfaces in a three-dimensional space (z, x, y). This function implicitly depends on the angle of control of the thyristors as it is defined by the formalized variables (x, y). The control surfaces $z(x, y)$ (Fig. 3), when the coefficient ν is increased, are shifted downwards and are transferred to the region of negative values earlier. The transition of the control surfaces to the region of negative values follows the curves $y(x)$ (Fig. 4), approximated in the region $0 < y \le 2\pi,\ \ 0 < x < \pi$ by the fifth-order polynomials using the least-squares method (Table 1). Substituting x and y in the polynomials with their values has produced the ratio for the boundary control surfaces that are explicitly dependent on angles α_1, α_2, α_3(Table 2). The boundary control surfaces $\alpha_{3lim} = f\left(\alpha_{1lim}, \alpha_{2lim}\right)$ split the three-dimensional space of opening angles of the commutation thyristors into two regions (Fig. 5). In the region where $\alpha_3 > \alpha_{3lim}$ the effective modes of STC operation are impossible. In the region where $\alpha_3 < \alpha_{3lim}$ the STC efficiency is determined by the distance between the control surface and a point in the three-dimensional space that characterizes the value of the angle α_3.

The application of a multi-coordinate control method has allowed me to improve the scheme of phase-to-phase control over the reactive power in an STC with the forced commutation and voltage addition (Fig. 6) in order to ensure the optimization of the compensator operation modes. That was due to the independent control over the commutation thyristors depending on the system's objective function. For the same purpose, the flowchart of the operating algorithm has been devised for the controlling microcontroller of the static compensator (Fig. 7).

When using the proposed circuit for an STC with the forced commutation, there is a need for a special design of the power transformer, which should provide the possibility to break the secondary windings of the transformer to connect the commutation thyristors to them.

The disadvantages of the proposed static compensator include a certain complexity of the reactive power controller, which requires the use of a power transformer. Further improvement of the current study could address the development of an alternative transformer-free controller, which would implement multi-coordinate control over reactive power and could achieve a decrease in the losses of active power.

8. Conclusions

1. A mathematical model of the static controller with phased control over reactive power has been proposed; the energy processes in it have been analyzed for the case of independent control over the commutation thyristors. The losses of reactive and active power were determined; the ways to reduce the specific losses of active power have been found, by changing the angles of control over the commutation thyristors and by using voltage addition during the action of a negative half-wave of the supply voltage.

2. A method of the multi-coordinate control over the reactive power of an STC with the forced commutation has been constructed; its essence implies an independent control over all commutation thyristors in accordance with the objective function of the system. It has been proposed to determine the objective function under the condition that the specific losses of active power during reactive power adjustment do not exceed their economically justified level. That makes it possible to implement the effective technologies of phase-to-phase control over reactive power.

3. The circuit of the phased control over reactive power in an STC with the forced commutation and voltage addition for networks with a compensated neutral has been improved. I have suggested a flowchart of the operation algorithm for the controlling static compensator's microcontroller, which makes it possible, during the adjustment of the reactive power, to reduce the specific losses of active power in the electrical network and compensator by increasing the voltage addition coefficient.

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