Flexible AC transmission systems that are built by using modern advances in power electronics are key components of smart grids. The object of research is a thyristor-controlled reactor, which is used as part of a static reactive power compensator to control the reactive power in the transmission and distribution electrical networks of power supply systems. It is proposed to use two-operation semiconductor gates in the regulator, which made it possible to obtain qualitatively new adjusting properties. The analysis of reactor power under the mode of phase control of the conductive state of gates by setting the moments of their closing time was carried out. Analytical expressions for angular power characteristics of the main harmonic were derived. It was revealed that by regulating, based on the phase principle, the conductive state of ideal semiconductor gates, which are switched on in series with ideal inductance, along with the adjustment of reactive power, the phenomenon of consumption of active power from the grid at the main harmonic is observed. It is shown that the reason for this is artificially obtained, with the help of semiconductor gates, active-inductive nature of the angle of displacement of the main harmonic of the current in the reactor relative to the voltage of the power supply. The study results prove the effect of adjusting the active power by a thyristor-regulated reactor. Research involving a virtual model illustrated the adjustment of the active power component of a synchronous generator by the effect on the rotor speed during gate adjustment of reactor power. The active power resource obtained in the process of thyristor adjustment of the reactor is commensurate with its installed capacity

Keywords: thyristor-controlled reactor, two-operation semiconductor gate, static reactive power compensator

UDC 621.316.761.2
DOI: 10.15587/1729-4061.2023.277908

POWER ANALYSIS OF THYRISTOR-REGULATED REACTOR WITH FULLY CONTROLLED SEMICONDUCTOR VALVES

Yevhen Fediv
Corresponding author
PhD, Associate Professor*
E-mail: yevhen.i.fediv@lpnu.ua
Olha Sivakova
PhD, Associate Professor*
*Department of Electric Power Engineering and Control Systems
Lviv Polytechnic National University
S. Bandery str., 12, Lviv, Ukraine, 79013

Received date 08.02.2023
Accepted date 14.04.2023
Published date 28.04.2023

How to Cite: *Fediv, Y., Sivakova, O. (2023). Power analysis of thyristor-regulated reactor with fully controlled semiconductor valves. Eastern-European Journal of Enterprise Technologies, 2 (8 (122)), 27–35. doi: https://doi.org/10.15587/1729-4061.2023.277908*

1. Introduction

The construction of active-adaptive intelligent networks (Smart Grid) with an open architecture, which flexibly connect elements of the electric power infrastructure to the network, is a characteristic trend of the current stage of development of the electric power industry in the world. They make it possible to increase the productivity and reliability of the operation of power supply systems while reducing their complexity.

Among the set of Smart Grid technologies that characterize the current stage of development of electric power infrastructure, a key role belongs to flexible AC transmission systems (Flexible Alternative Current Transmission System, FACTS) [1], which improve the performance parameters of power systems. FACTS devices are designed using modern achievements of power electronics. First of all, they perform the task of ensuring balances of active and reactive power. Also, FACTS devices are an effective resource for solving problems of improving the quality of consumer supply voltage, ensuring the sustainability of power transmission and distribution systems, increasing energy efficiency and reliability of power supply systems.

Therefore, investigating ways to regulate and convert electrical power, expand functionality, as well as improve the efficiency of FACTS devices is a relevant task.

2. Literature review and problem statement

To adjust the power in electricity supply systems, power static semiconductor converters are used. The latest achievements in this area are associated with the use of modern achievements in the field of power electronics [2–4].

In [2], the demand and application of power electronics technologies in smart grids are analyzed. Studies [3, 4] describe the resources of power electronics and the characteristics of power converters used in distributed generation systems of microgrids and intelligent networks to convert the received energy into usable power. The importance and ability of individual resources to regulate the flows of active and reactive power, as well as the energy efficiency obtained from this, are noted. Thus, modern progress in the development of the element base and technologies of power electronics is the basic component and marker of Smart Grid. However, among the element base of power electronics, today, there are power single-operation semiconductor gates, controlled by the delay of their opening, but there are no single-operation semiconductor gates controlled by the advance in their closure. This function can be implemented only on the basis of two-operation thyristors or transistors.

In [5, 6], it is noted that given the pace of improvement of FACTS devices, dynamic compensation of reactive power is one of the key technologies and a key method for increasing reliable AC networks. But no less important is the dynamic balancing of active power, especially in complex combination.

In [7, 8], the effectiveness of dynamic compensation of reactive power to improve the quality of transients during emergencies in the electric power system is illustrated. Possible strategies for adjusting shunt reactors are being considered, but only on the basis of single-operation semiconductor gates.

Dynamic adjustment of reactive power flows in Smart Grid technology is provided mainly by Static Synchronous Compensator (STATCOM) and Static VAR Compensator (SVC) [9]. These two types of compensators are marked as basic FACTS devices. STATCOM is built on fully controlled semiconductor gates and is able to regulate flows of both active and reactive power. SVC uses semi-controlled thyristors and it regulates only the flow of reactive power.

In [10], a hybrid static converter (STATCOM and SVC) with the function of dynamic compensation of reactive power without significant harmonic current distortion, as opposed to SVC, is proposed. Using STATCOM as an active filter, it is possible to level the problem of harmonic SVC current distortion, which expands the scope of its practical use.

In [11], a review is presented with a comparison of FACTS devices capable of adjusting active and reactive power flows to increase the stability of the power system. It is shown that the most effective for maintaining voltage stability is the use of the integrated power flow regulator – STATCOM together with longitudinal thyristor compensation. In [12], the advantages of SVC and STATCOM are proved to solve the problem of ensuring stability and voltage stability margin in the power system. In [13], it is substantiated that STATCOM is the most effective application to ensure the quality of electricity in power systems with renewable sources, especially when paired with an accumulator (E-STATCOM). Thus, for a wide range of Smart Grid tasks solved by FACTS, SVC and STATCOM devices are competitive but SVC does not fit into such strategic principles of Smart Grid concept as Distributed Generation, Renewable Generation, and Energy Storage.

STATCOM belongs to the class of static semiconductor voltage converters built using modern power fully controlled semiconductor gates – transistors or thyristors, with the ability to regulate flows of both reactive and active power. The work of STATCOM is based on the semiconductor conversion of a constant voltage of an energy source into an alternating sinusoidal voltage of a given amplitude and phase. The nature of energy exchange between the power system and STATCOM depends on the ratio of amplitudes and phases of the alternating voltage at the output of STATCOM and the voltage at the point of its connection to the power system [14, 15]. STATCOM is a multifunctional, complex, and still expensive FACTS device [16]. It is obvious that the use of STATCOM is a responsible and costly investment project, the implementation of which requires a feasibility study. In this regard, at a certain stage in the development of power grids, a competitor to STATCOM may be a less costly option of upgrading existing resources of the FACTS class.

In [17], the results of modeling static and dynamic modes of SVC using the application resource Matlab/SimPowerSystems by The MathWorks are reported. SVC in the FACTS device system performs the function of a smoothly adjustable high-speed reactive power source of both signs. SVC is especially effective for dynamic compensation of reactive power and maintaining the proper voltage level in power transmission and distribution systems, as well as for smoothing voltage flickers in industrial power consumption systems with powerful sharply changing loads. SVC is a relatively inexpensive multifunctional device, the ability to adjust which is implemented on the principle of phase control of single-operation voltage thyristors on a shunt reactor. However, its competitiveness is limited by the fact that it is not able to directly regulate the flow of active power in systems providing consumers with electricity.

SVC and STATCOM are implemented in many projects but, unlike STATCOM, SVC is not able to directly regulate active power flows. This is its limitations as a FACTS device.

In [18, 19], the results of the study of phase control modes by two-operation thyristors and power components of the resistive shunt element of the power grid are reported, and in [20] – the shunt element of the capacitive power grid. In the above studies, there is no information on the effectiveness of a possible similar adjustment of an inductive shunt element.

In general, the possibilities of phase control of TCR gates have not been studied in detail. Therefore, it is advisable to analyze the power of an upgraded TCR equipped with two-operation semiconductor gates. The resulting energy characteristics should become the basis for outlining the scope and selection of optimal SVC adjustment modes by operators of transmission and distribution systems.

3. The aim and objectives of the study

The aim of this study is to establish the features of TCR power adjustment controlled by modern two-operation semiconductor gates. This will make it possible to specify the effectiveness and outline the technical feasibility of replacing single-operation thyristors TCR with fully controllable ones.

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

– to analyze electromagnetic processes and derive expressions for the energy characteristics of TCR, regulated by the delay of opening and natural closing of fully controlled thyristors;

– to analyze electromagnetic processes and derive expressions for the energy characteristics, regulated by the advance of closing and natural opening of fully controlled thyristors.

4. The study materials and methods

The object of research is TCR, which is an integral part of SVC. The main elements of SVC are a thyristor-controlled reactor (TCR) and a thyristor switched capacitor battery. TCR is made according to the scheme of a semiconductor alternating voltage regulator with an inductive load. In series with the shunt reactor, counter-parallel semi-controlled semi-conductor gates connected to each other according to the phase principle are turned on.

The main hypothesis of the study is to clarify the possibility of adjusting the active component of power in the power supply system with TCR. The studies were carried out by mathematical modeling of steady-state modes for the predefined technique of phase control over semiconductor gates. Similar to [20], two techniques of phase control over thyristors were investigated: delay of opening time points and advance in the moments of their closing time. These control techniques are essentially single-operational, but it is possible to comprehensively implement them, at present, only on the basis of fully controlled semiconductor gates. The assumptions of sinusoidality of the shape of supply voltage, the absence of losses in the elements of TCR in single-phase execution, and the instantaneousness of switching thyristors were accepted. Our results were checked by simulating the modes in the application package SimPowerSystem of the visual programming environment Simulink of the Matlab software package (USA).

5. Results of the study of established modes of TCR operation with fully controlled thyristors

5. 1. Analysis of TCR mode with adjustable thyristor opening delay

Equivalent scheme of TCR one phase with two-operation thyristors is shown in Fig. 1. Fig. 2 shows the time diagrams of TCR voltages and currents under the thyristor adjustment mode by specifying angles α of their opening.

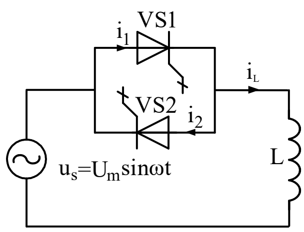

Fig. 1. Equivalent circuit of a single phase of the thyristor-controlled reactor SVC

For time intervals with the conductive state of TCR thyristors, the following equations hold:

$$\begin{cases} u_s = U_m \sin \omega t, \\ L\dfrac{di_L}{dt} = U_m \sin\omega t. \end{cases} \quad (1)$$

The general expression for reactor current from equations (1) is:

$$i_L = -\frac{U_m}{\omega L}(\cos\omega t - C), \quad (2)$$

where C is the integration constant, the value of which is obtained from the initial conditions.

If thyristor $VS1$ opens by a control pulse at time α with a delay relative to the natural moment of time of its opening $\omega t_{on}=\pi/2$, then it closes on its own. This will happen at time β_{off}, before the natural moment of its closure time $\omega t_{off}=3\pi/2$ (Fig. 2, *c*).

If thyristor $VS1$ opens by a control pulse at time α with a delay relative to the natural time of its opening $\omega t_{on}=\pi/2$, then it closes independently at time β_{off}, earlier than the natural moment of its closing time $\omega t_{off}=3\pi/2$ (Fig. 2, *c*). At an opening angle of $\alpha=\pi/2$, the thyristors are completely open, and the reactor current is sinusoidal. In the case of the opening angle of $\alpha=\pi$, the thyristors are closed and there is no current in the reactor. Thus, the total range of change of thyristor control angles is $\alpha=\pi/2\div\pi$ rad. In the process of adjusting the angle α, the value of the shear angle of the main harmonic of the reactor current relative to the supply voltage is constant and is equal to $\varphi_{(1)}=\pi/2$ rad (Fig. 2, *e*).

Taking into account the condition $i_L(\alpha)=0$ (Fig. 2, *e*), expression (2) takes the form:

$$i_L = i_1 = \frac{U_m}{\omega L}(\cos\alpha - \cos\omega t). \quad (3)$$

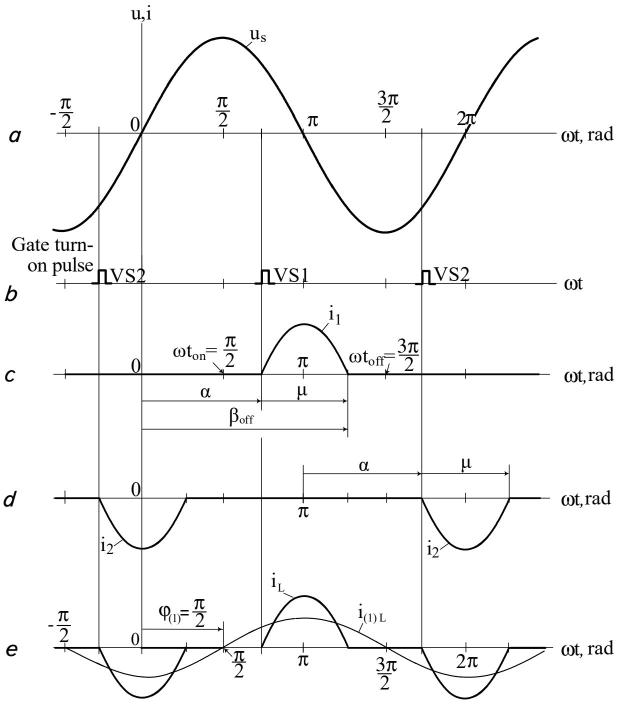

Fig. 2. Time diagrams of thyristor-controlled reactor under the control mode of single-operation thyristors of the regulator: *a* – power supply voltage; *b* – thyristor opening control pulses; *c*, *d* – thyristor currents; *e* – reactor current

The value of the thyristor closing angle $VS1$ is obtained from (3), substituting the condition $i_L(\alpha)=i_L(\beta_{off})$.

As a result, we get:

$$\beta_{off} = 2\pi - \alpha, \quad (4)$$

and the duration of the thyristor conductive state will be:

$$\mu = 2(\pi - \alpha). \quad (5)$$

In order to derive expressions for energy characteristics, we expand the expressions for current i_L into the Fourier series. As a result, the following equations are obtained for the coefficients of the series:

$$a_n = \frac{2}{T}\int_0^T i_L(\omega t)\cos n\omega t \, d\omega t =$$
$$= \frac{1}{\pi}\left\{\int_{\alpha}^{2\pi-\alpha} i_1(\omega t)\cos n\omega t d(\omega t) + \int_{\alpha+\pi}^{3\pi-\alpha} i_2(\omega t)\cos n\omega t d(\omega t)\right\} =$$
$$= \frac{U_m}{\pi\omega L}\left\{\begin{aligned}&\int_{\alpha}^{2\pi-\alpha}(\cos\alpha - \cos\omega t)\cos n\omega t d(\omega t) + \\ &+\int_{\alpha+\pi}^{3\pi-\alpha}\left[\cos(\alpha+\pi) - \cos\omega t\right]\cos n\omega t d(\omega t)\end{aligned}\right\}, \quad (6)$$

$$b_n = \frac{2}{T}\int_0^T i_L(\omega t)\sin n\omega t d\omega t =$$
$$= \frac{1}{\pi}\left\{\int_{\alpha}^{2\pi-\alpha} i_1(\omega t)\sin n\omega t d(\omega t) + \int_{\alpha+\pi}^{3\pi-\alpha} i_2(\omega t)\sin n\omega t d(\omega t)\right\} =$$
$$\frac{U_m}{\pi\omega L}\left\{\begin{aligned}&\int_{\alpha}^{2\pi-\alpha}(\cos\alpha - \cos\omega t)\sin n\omega t d(\omega t) + \\ &+\int_{\alpha+\pi}^{3\pi-\alpha}\left[\cos(\alpha+\pi) - \cos\omega t\right]\sin n\omega t d(\omega t)\end{aligned}\right\}. \quad (7)$$

For $n=1$, from equations (6), (7), we obtain:

$$a_1 = \frac{U_m}{\pi\omega L}\left[2(\pi-\alpha)-\sin 2\alpha\right], \quad (8)$$

$$b_1 = 0. \quad (9)$$

Fundamental reactive power of TCR (reactive power at base frequency), according to [21]:

$$Q_1 = \frac{U_m I_{1m}}{2}\sin\varphi_1, \quad (10)$$

where I_{1m} is the amplitude of the main harmonic of the current, φ_1 is the phase angle between the main harmonic of the current and the supply voltage, which are derived from expressions known in mathematics:

$$I_{1m} = \sqrt{a_1^2 + b_1^2}, \quad (11)$$

$$\varphi_1 = \mathrm{arctg}\left(\frac{b_1}{a_1}\right). \quad (12)$$

Substituting (8), (9) in (11), (12), we get:

$$I_{1m} = \frac{U_m}{\pi\omega L}\left[2(\pi-\alpha)-\sin 2\alpha\right], \quad (13)$$

$$\varphi_1 = \frac{\pi}{2} = \mathrm{const}. \quad (14)$$

Hence, an important conclusion: TCR operates with a constant angle φ_1, the value of which does not depend on the angle α of thyristor control. In accordance with (10), taking into account (13), (14), we obtain that the shunt reactor consumes reactive power from the power supply network at the main harmonic:

$$Q_1 = \frac{U_m^2}{2\pi\omega L}\left[2(\pi-\alpha)-\sin 2\alpha\right]. \quad (15)$$

Fig. 3 shows the dependence, calculated from (15), of the relative value of reactive power $Q_{1*}=Q_1/Q_b$, which is consumed by the reactor, on the value of the angle α of thyristor opening.

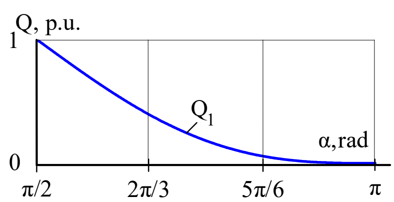

Fig. 3. Angular characteristic of reactive power for the main harmonic of TCR with single-operation thyristors

The adopted base power is its value for $\alpha=\pi/2$, that is, $Q_b = U_m^2/(2\omega L)$.

5. 2. Analysis of TCR mode with thyristor closing advance adjustment

Two-operation thyristors are suitable for implementing a technique of adjusting TCR by closing them early with a control current and opening at the time of appearance of a positive anode voltage. As a result of the study, it was established that the total range of change in closing angles β is $0\leq\beta\leq 3\pi/2$, which by the nature of electromagnetic processes can be divided into two sub-ranges. The first is for the thyristor closing angles within $\pi\leq\beta\leq 3\pi/2$, and the second – for angles $0\leq\beta<\pi$.

Fig. 4 shows the time diagrams of TCR voltages and currents under the adjustment mode characteristic of the range of values of closing angles $\pi\leq\beta\leq 3\pi/2$.

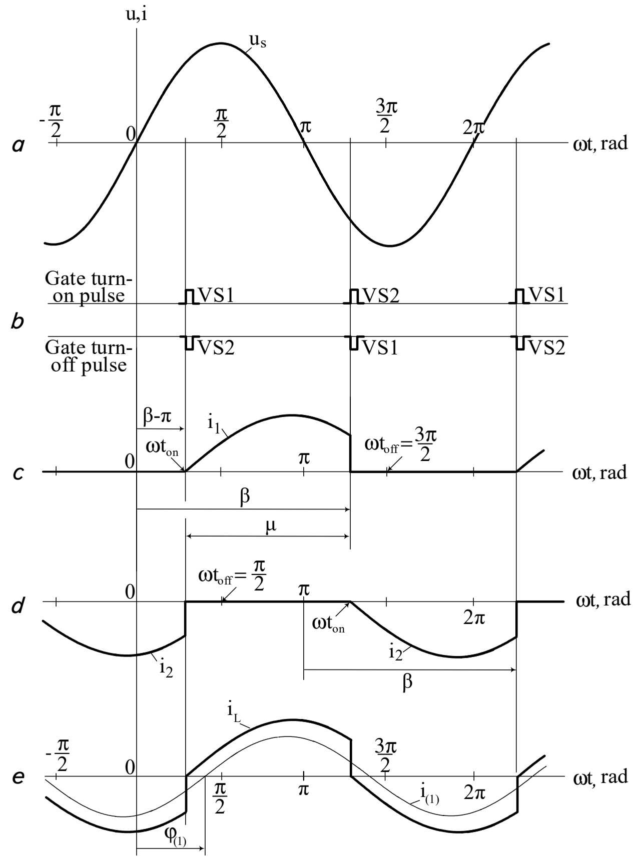

Fig. 4. Time diagrams of currents and voltages of TCR under the control mode of closing thyristors angles $\beta>\pi$: *a* – voltage of the power supply; *b* – thyristor state control pulses; *c*, *d* – currents of thyristors; *e* – reactor current

Thyristor VS1 closes by the control pulse at the predefined point in time $\omega t=\beta$ with an advance relative to the natural moment of time of its closure $\omega t_{\mathrm{off}}=3\pi/2$, and it opens at time $\omega t_{\mathrm{on}}=\beta-\pi$, which corresponds to the duration of the thyristor conductive state $\mu=\pi$ rad (Fig. 4, *c*).

The study found that in the process of reducing the value of the angle β there is an invariance of the duration of the conductive state of the thyristor, that is, $\mu=\pi=\mathrm{const}$. However, there is a shift in the time interval of the thyristor conductive state and, accordingly, a decrease in angle $\varphi_{(1)}$ between the main harmonic of the reactor current and the supply voltage (Fig. 4, *e*).

As a result, we obtain the value of angle $\varphi_{(1)}<\pi/2$, which indicates the appearance of a fundamental active component of power, or active power at the frequency of the power system [21].

For the mathematical estimation of the above qualitative picture of electromagnetic processes, we expand equation (2) into the Fourier series for current i_L, obtained by solving (1), taking into account the initial conditions for the time moments when thyristors start operation (Fig. 4, *c–e*). As a result, we derive the following expressions for the coefficients of the series:

$$a_n=\frac{2}{T}\int_0^T i_L(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)=$$
$$=\frac{1}{\pi}\left[\int_{\beta-\pi}^{\beta} i_1(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)+\int_{\beta}^{\beta+\pi} i_2(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)\right]=$$
$$=\frac{U_m}{\pi\omega L}\left\{\begin{array}{l}\int_{\beta-\pi}^{\beta}\left[\cos(\beta-\pi)-\cos\omega t\right]\cos n\omega t\,\mathrm{d}(\omega t)+\\+\int_{\beta}^{\beta+\pi}(\cos\beta-\cos\omega t)\cos n\omega t\,\mathrm{d}(\omega t)\end{array}\right\}=$$
$$=\frac{U_m}{\pi\omega L}\left\{\begin{array}{l}\frac{2\cos\beta\sin(n\beta)}{n}\left[\cos(n\pi)-1\right]-\\-\sin(n\pi)\left[\frac{\cos\left[(n-1)\beta\right]}{n-1}-\frac{\cos\left[(n+1)\beta\right]}{n+1}\right]\end{array}\right\}, \quad (16)$$

$$b_n=\frac{2}{T}\int_0^T i_L(\omega t)\sin n\omega t\,\mathrm{d}(\omega t)=$$
$$=\frac{1}{\pi}\left[\int_{\beta-\pi}^{\beta} i_1(\omega t)\sin n\omega t\,\mathrm{d}(\omega t)+\int_{\beta}^{\beta+\pi} i_2(\omega t)\sin n\omega t\,\mathrm{d}(\omega t)\right]=$$
$$\frac{U_m}{\pi\omega L}\left\{\begin{array}{l}\int_{\beta-\pi}^{\beta}\left[\cos(\beta-\pi)-\cos\omega t\right]\sin n\omega t\,\mathrm{d}(\omega t)+\\+\int_{\beta}^{\beta+\pi}(\cos\beta-\cos\omega t)\sin n\omega t\,\mathrm{d}(\omega t)\end{array}\right\}=$$
$$\frac{U_m}{\pi\omega L}\left\{\begin{array}{l}\frac{2\cos\beta\cos(n\beta)}{n}\left[1-\cos(n\pi)\right]+\\+\sin(n\pi)\left[\frac{\sin\left[(n-1)\beta\right]}{n-1}-\frac{\sin\left[(n+1)\beta\right]}{n+1}\right]\end{array}\right\}. \quad (17)$$

For $n=1$, from equations (16), (17), we obtain expressions for the coefficients of the basic harmonic of the Fourier series:

$$a_1=\frac{U_m}{\pi\omega L}(\pi-2\sin 2\beta), \quad (18)$$

$$b_1=\frac{4U_m}{\pi\omega L}\cos^2\beta. \quad (19)$$

Fig. 5 shows the time diagrams of voltages and currents of TCR under the control mode of two-operation thyristors by specifying angles β of their closure, characteristic of the range of values of angles $0<\beta<\pi$.

At closing angles $\beta<\pi$, the natural angle of thyristor *VS*1 opening remains equal to $\omega t_{\text{on}}=0$ and the duration of the conductive state is equal to the closing angle ($\mu=\beta$), that is, the thyristors of the reactor conduct at the predefined angle of their closure but a constant angle of their opening (Fig. 5, *c, d*). Reducing the duration of the conductive state of thyristors with decreasing angle β at a fixed moment in time of their opening leads to a decrease in the phase angle between the main harmonic of reactor current and power supply voltage.

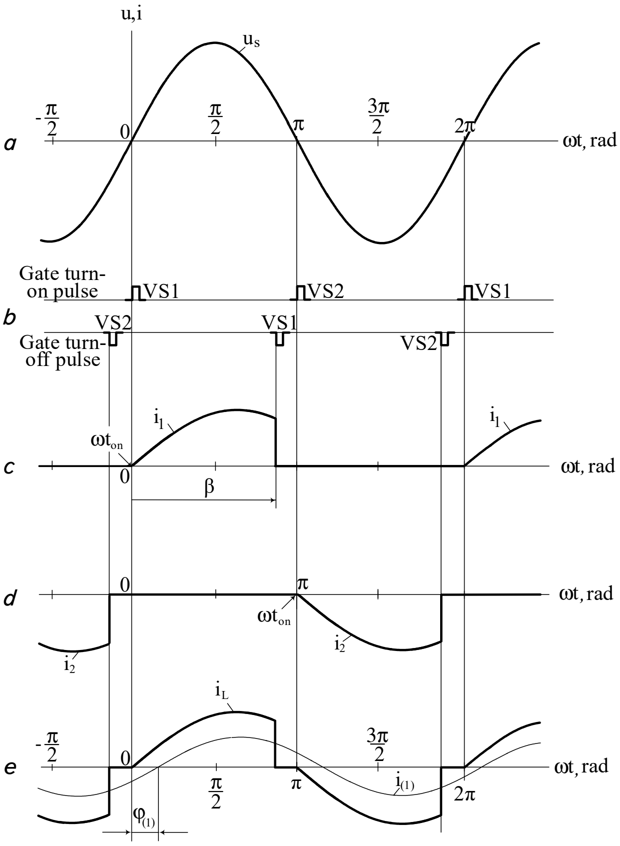

Fig. 5. Time diagrams of currents and voltages of TCR under the mode of adjusting the angles of closing thyristors $\beta<\pi$: *a* — voltage of the power supply; *b* — thyristor state control pulses; *c, d* — currents of thyristors; *e* — reactor current

The derived expressions for expansion coefficients into the Fourier current series for the TCR mode with the control angle $\beta<\pi$ take the form:

$$a_n=\frac{2}{T}\int_0^T i_L(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)=\frac{1}{\pi}\left[\int_0^{\beta} i_1(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)+\int_{\pi}^{\pi+\beta} i_2(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)\right]=$$
$$=\frac{U_m}{\pi\omega L}\left\{\int_0^{\beta}\left[1-\cos\omega t\right]\cos n\omega t\,\mathrm{d}(\omega t)-\int_{\pi}^{\pi+\beta}(1+\cos\omega t)\cos n\omega t\,\mathrm{d}(\omega t)\right\}=$$
$$=\frac{U_m}{\pi\omega L}\left\{\begin{array}{l}\frac{\sin\beta-\sin\left[n(\pi+\beta)\right]+\sin(n\pi)}{n}-\\-\frac{\sin\left[(1-n)\beta\right]+\sin\left[(1-n)(\pi+\beta)\right]-\sin\left[(1-n)\pi\right]}{2(1-n)}-\\\frac{\sin\left[(1+n)\beta\right]+\sin\left[(1+n)(\pi+\beta)\right]-\sin\left[(1+n)\pi\right]}{2(1+n)}\end{array}\right\}, \quad (20)$$

$$b_n=\frac{2}{T}\int_0^T i_L(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)=\frac{1}{\pi}\left[\int_0^{\beta} i_1(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)+\int_{\pi}^{\pi+\beta} i_2(\omega t)\cos n\omega t\,\mathrm{d}(\omega t)\right]=$$
$$=\frac{U_m}{\pi\omega L}\left\{\int_0^{\beta}\left[1-\cos\omega t\right]\cos n\omega t\,\mathrm{d}(\omega t)-\int_{\pi}^{\pi+\beta}(1+\cos\omega t)\cos n\omega t\,\mathrm{d}(\omega t)\right\}=$$
$$=\frac{U_m}{\pi\omega L}\left\{\begin{array}{l}\frac{1-\cos(n\beta)}{n}+\frac{\cos\left[n(\pi+\beta)\right]-\cos(n\pi)}{n}-\\-\frac{1-\cos\left[(n-1)\beta\right]-\cos\left[(n-1)(\pi+\beta)\right]+\cos\left[(n-1)\pi\right]}{2(n-1)}-\\-\frac{1-\cos\left[(n+1)\beta\right]-\cos\left[(n+1)(\pi+\beta)\right]+\cos\left[(n+1)\pi\right]}{2(n+1)}\end{array}\right\}. \quad (21)$$

For $n=1$, from equations (18), (19), we obtain the following expressions for the coefficients of the basic harmonic of the Fourier series:

$$a_1=\frac{U_m}{\pi\omega L}\left(2\sin\beta-\frac{\sin 2\beta}{2}-\beta\right), \tag{22}$$

$$b_1=\frac{U_m}{\pi\omega L}(\cos\beta-1)^2. \tag{23}$$

Calculated according to (12), using (18), (19), (22), (23), the dependence of the shear angle of the main harmonic of the reactor current relative to the supply voltage is shown in Fig. 6. It characterizes the components of TCR power with two-operation thyristors for the full range of adjustment of thyristor closing angle.

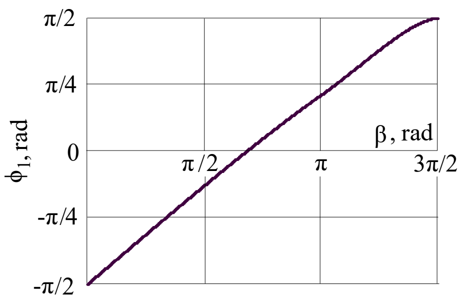

Fig. 6. Phase angle φ_1 of the main TCR current harmonic for a full range of angle β adjustment

The derived value of angle φ_1 in the range of values $-\pi/2\le\varphi_1\le\pi/2$ means that the operation of TCR is characterized not only by reactive but also by the active component of power. TCR consumes from the power supply the active component of the fundamental power, which is calculated from the following formula [21]:

$$P_1=\frac{U_m I_{1m}}{2}\cos\varphi_1. \tag{24}$$

Fig. 7 shows the angular characteristics of reactive and active power for the full range of values of TCR thyristor closing angle, calculated using expressions (10) to (12), (18), (19), (22) to (24).

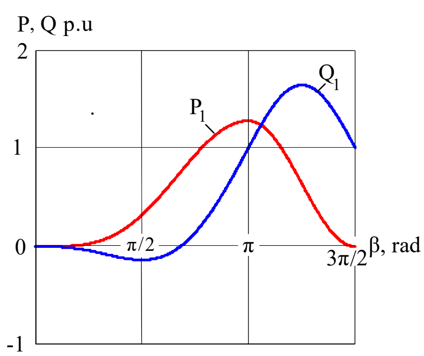

Fig. 7. Angular characteristics of the fundamental values of reactive Q_1 and active P_1 power of TCR with two-operation thyristors

As can be seen from Fig. 7, the reactor, controlled by the closure of two-operation thyristors, consumes power from the grid, along with the fundamental reactive power, the fundamental active power as well. The maximum active power consumption is 1.27 p.u. and is observed at a closing angle of β=π rad.

To verify our results regarding the TCR power analysis, a study of the mode of the power plant unit was carried out, the turbine T of which drives the rotor of the three-phase synchronous generator GS (Fig. 8). From the generator, it receives power static active load R. To the generator, shunting apparatus Q can connect a shunt reactor L, regulated by two-operation thyristors VS1, VS2 using CS control system.

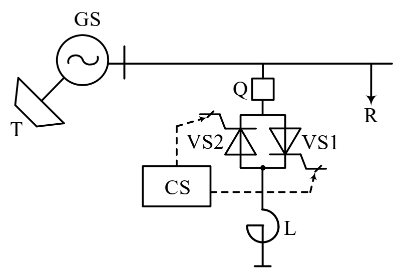

Fig. 8. Schematic diagram of the electrical system

The experimental study is implemented on the developed virtual model in the visual programming environment Simulink of the application package Matlab for the analysis of dynamical systems (Fig. 9). With the help of a computer experiment, the influence of TCR input with fully controlled thyristors on the power and frequency of voltage at the terminals of an unregulated synchronous generator was investigated. In order to increase the degree of adequacy of the experiment, a model of a synchronous generator with a nominal frequency of 60 Hz, a power of 187 MVA, and a voltage of 13.8 kV was borrowed from the SimPowerSystem software library for applied problems of the Simulink environment of Mathwork corporation (USA). The finished model of the generator, without making changes to it, together with the means of measuring and visualizing the operating mode, is mounted into the model of the power system (Fig. 9).

The main results of the experiment in the form of time diagrams of the parameters of the generator mode are shown in Fig. 10.

At time $t=0$, the synchronous generator, the rotor of which is driven by a 15 MW turbine, is switched on for a three-phase active static load with a capacity of 10 MW. The mode is characterized by an imbalance in the generation and consumption of active power, a value of 5 MW. Under the influence of excess generation power over a time interval of 0.5 s, the voltage frequency increases from 60 Hz to 60.1 Hz (Fig. 10, *c*). At time $t_1=0.5$ s the circuit breaker activates a three-phase shunt reactor with an inductance of 0.05 H, controlled by two-operation thyristors with closing angles β=π rad. As a result, the reactor generates about 13 MVAr of reactive power (Fig. 10, *b*). At the same time, the generator load with active power increases from 10 MW to about 20 MW (Fig. 10, *a*), which is equivalent in energy effect to adding an additional active load of about 10 MW.

Now, under the influence of a shortage of generation power (5 MW), the frequency value in the system begins to decline. At time $t_2=1.0$ s, when the frequency approaches the level of 60 Hz, the reactor is switched off by the circuit breaker and, under the influence of excess generation power, the voltage frequency begins to increase again.

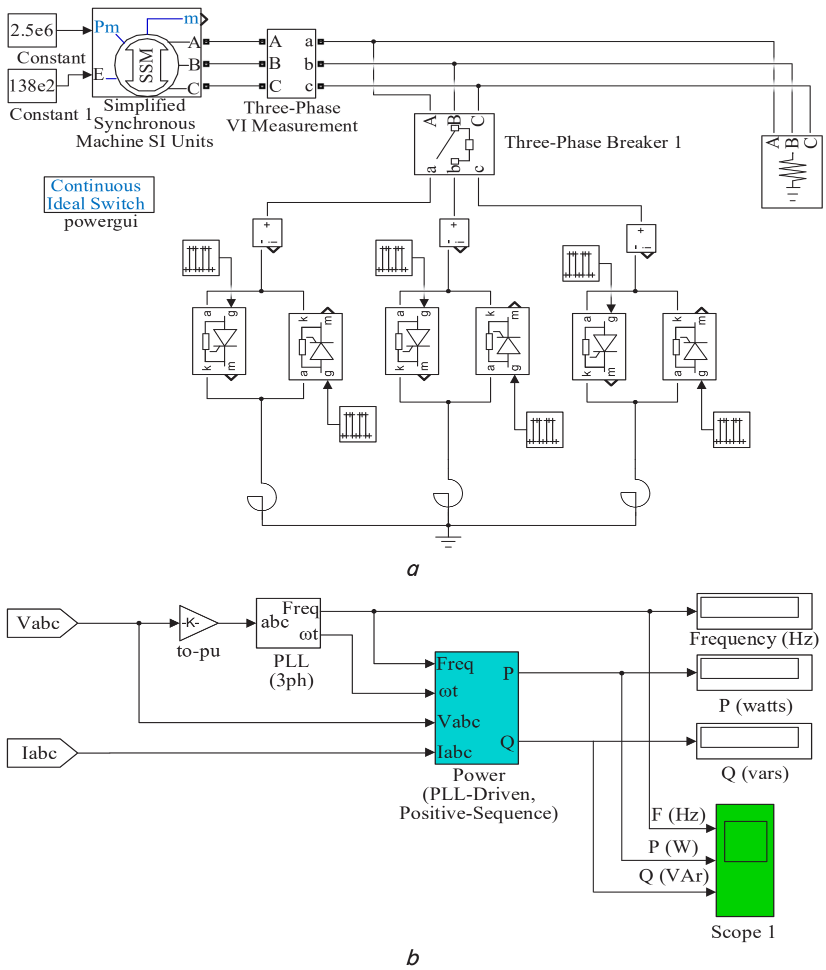

Fig. 9. Simulink model of power system with thyristor-controlled reactor: *a* — diagram of the power part of the model; *b* — measurement scheme

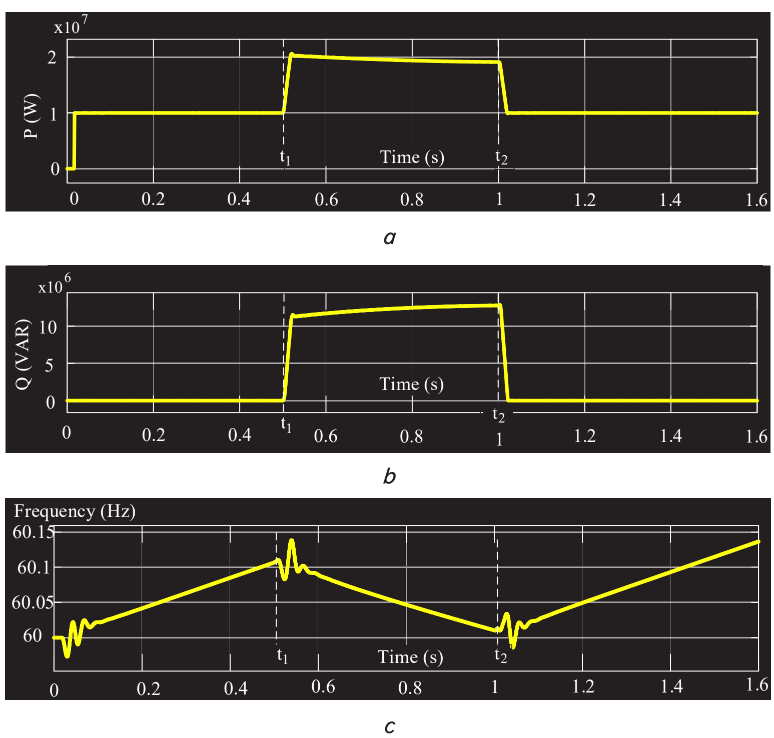

Fig. 10. Time diagrams of synchronous generator mode parameters: *a* — active power according to the main harmonic; *b* — reactive power for the main harmonic; *c* — frequency

6. Discussion of the study of power components of a thyristor-controlled reactor with fully controlled semiconductor gates

Equipping TCR, which belong to the SVC reactive power and equipped with traditional single-operation thyristors, with fully controlled semiconductor gates expands their functionality as the possibilities of phase adjustment of thyristors in TCR are expanded. Along with the main function – consumption in the electric power system of excess volumes of reactive power, we get the possibility of consuming excess volumes of active power, which is generally not peculiar to SVC. This is important when you consider that SVC projects have been implemented worldwide with a total capacity of more than 100 GVA, and they were the first devices to meet the requirements of FACTS.

The current study showed that the phase adjustment of TCR based on single-operation thyristors with a delay in their operation, that is, in the direction of the natural current shift in the inductance, is accompanied by a constant angle of shift of the fundamental component of the current $\varphi_{(1)}=\pi/2$ rad.

This is due to the fact that the opening of thyristors with a delay relative to the natural angle of opening at angle $\alpha-\omega t_{on}$ is accompanied by their advance in closing relative to the natural moment of time of their closing by the same value of angle ωt_{off}-β (Fig. 2, *c*). As a result, in the process of increasing the control angle α, the duration of μ of the thyristor conductive state decreases, and the value of the shear angle of the main harmonic of the reactor current is unchanged (Fig. 2, *e*). The main harmonic of the reactor current is purely inductive in nature over the entire range of control angles. TCR consumes reactive power from the power supply.

The use of two-operation thyristors allowed us to change the way of phase control over TCR thyristors. The opening of thyristors at the natural angle of operation and closing ahead of the natural angle of closure, made it possible to obtain modes with an actively inductive nature of current in the reactor.

In the process of adjusting the angle β ahead of the thyristor closure, the value of angle $\varphi_{(1)}$ is not constant but it changes. For the angle of closing thyristors $\beta=3\pi/2$ rad, the value of angle $\varphi_{(1)}=\pi/2$ rad, the current in the reactor is sinusoidal and inductive in nature. The reactor consumes reactive power from the power supply. For the closing angle range $\pi\leq\beta\leq3\pi/2$ with decreasing angle β the duration of the thyristor conductive state remains unchanged ($\mu=\pi$, Fig. 5, *c*) since this decreases the natural angle of their opening $\omega t_{on}=\beta-\pi$. As a result, there is a shift in the interval of the conductive state of thyristors in the direction of advance, which leads to a decrease in the angle $\varphi_{(1)}<\pi/2$. The main harmonic current in the reactor is actively inductive, up to the value of the angle $\beta=2\pi/3$ rad. In addition to reactive power, the reactor consumes from the grid the active power at the main harmonic. For closing angles $\beta=2\pi/3$ rad, the main harmonic current in the reactor coincides in phase with the voltage of the power supply ($\varphi_{(1)}=0$) and the reactor consumes only active power from the network. With a further decrease in the closing angles ($0\leq\beta<2\pi/3$), the current in the reactor is active-capacitive ($\varphi_{(1)}<0$, Fig. 7).

The maximum consumption of active power by the reactor corresponds to the closing angle of thyristors $\beta=\pi$. It can be assumed that in this case the advance of closing thyristors at angle $\omega t_{off}-\beta=\pi/2$ rad compensates for the natural inductive delay of the main harmonic current in the reactor at angle $\pi/2$ rad.

As a result of the mathematical modeling, an uncharacteristic for ideal inductance, regulated by ideal key elements, the active component of power consumed from the power supply network was revealed. The appearance of uncharacteristic power components for static elements regulated by two-operation thyristors is associated with an artificial phase shift of the main current harmonic. This is confirmed by research reported in [21–23].

With the help of a computer experiment, the manifestation of the active component of power in the form of the influence of TCR operation on the voltage frequency and rotational speed of the rotor of a synchronous generator has been proved. Switching on the reactor regulated by the proposed technique of phase control over the state of conductivity of thyristors leads to the appearance of an additional component of the electromagnetic moment of the synchronous generator and contributes to its braking. This means an additional load of the generator with active power at the main harmonic.

The disadvantage that should be taken into account when trying to apply the improved TCR in practice is the possibility of complex transients caused by the presence of a parallel-connected capacitor battery in SVC. Obviously, separate studies should be carried out and the efficiency and feasibility of the presence of a capacitor battery should be clarified at the time of switching TCR to the adjustment mode of the active power component.

The development of our research may be a feasibility study into the expediency of upgrading operating SVC by replacing single-operation thyristors with fully controllable ones.

7. Conclusions

1. Our analysis of electromagnetic processes of thyristor-controlled reactor with fully controlled thyristors showed the possibility of improving SVC as a Smart Grid resource for adjusting both reactive and active power.

2. Phase technique of adjustment of two-operation SVC thyristors can produce a resource of active power, commensurate with its installed power and suitable for balancing excess active power in the electric power system.

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.

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