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Modeling of an Active Reactive Power Compensator Operation in an Autonomous Electric Power System

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***Abstract*—This paper presents the results of a model-based studies on the efficiency of using a static thyristor reactive power compensator in an autonomous electric power system to increase the power factor, which has a positive effect on the autonomous electric power system efficiency. In order to restore the sinusoidal waveform of the network voltage distorted by the interference generated by a static thyristor compensator, the use of combined passive and active filtering during operation was employed. Block diagrams of all the constituent elements of the system, namely a static thyristor compensator, an active filter based on a thyristor converter, and an automatic control system have been developed. A MATLAB model of a reactive power compensator was developed and results of the simulating the model were obtained on the basis of block diagrams. Simulation of the system showed that for a load with a power factor of 0.5–0.6, it is possible to ensure operation with a power factor of 0.8–0.95 with a THD of consumed current in the range of 10%–25%. It has been found that an effective means of eliminating rectified voltage ripple is a cascade connection of an LC filter and an active filter, effectively attenuates harmonics from 4 to 50 by 40 dB. At the same time, a decrease in the cutoff frequency of the active filter leads to an increase in the effective time constant, which has a negative impact on the operating speed of the entire system. To eliminate this shortcoming, the control system is introduced with backward linkages, while precise compensation is carried out by several control loops according to the principle of subordinate control.**

***Index Terms*—Active filter, modeling, power efficiency, reactive power, static thyristor compensator**

I. INTRODUCTION

At the present stage of the world electric power industry development, drastic transition to energy-saving technologies is necessary. The transition to various methods of reducing electrical energy losses, which would decrease the need for implementing new generating capacities and fossil fuel necessary for them [1, 2]. The flow of reactive power in power systems produces significant effects on the optimal functioning of suppliers and customers which are connected [3]. One of the main issues that must be resolved at the stage of industrial power supply systems design and operation is the issue of reactive power compensation. The growth in reactive power consumption exceeds active power consumption growth. This is caused by the rapid development of new lighting and advertising systems, static power supply units for computer equipment, frequency converters for electric drives using non-linear elements for operation, and by many other reasons [4, 5].

There are a number of reactive power compensation devices, which can be divided into passive, active and hybrid devices. Compared with passive compensating devices, the most effective in 0.4 kV networks at present is the use of active compensators, the operation of which as part of electrical complexes, which include an electrical network and a load, makes it possible to ensure smooth regulation of the magnitude of the reactive component of the current, while not generating higher harmonic currents to the network. At the same time, the use of active compensators is not always economically justified, and traditional passive compensating devices do not meet modern requirements for the smoothness and speed of reactive power control or can worsen the spectral composition of the network current. Thus, given the role played by reactive power compensation devices, research aimed at improving the power factor of electrical complexes is a priority.

Practical application and research of static thyristor compensators (STC), accomplished by various known electrical engineering stake-holders (ABB, General Electric, Schneider Electric, Mitsubishi, Siemens, Westinghouse, Hitachi Energy, etc.) have shown that STC designs based on the thyristor-controlled shunt reactors, on the so-called thyristor-reactor groups, and higher harmonics parallel filters, commonly called a compensating filter [6, 7] are most suitable for use in power supply systems. In Jordan, Ukraine and many other countries, a full range of scientific research, design, and engineering development related to this field is being carried out [8, 9], which proves the relevance of this study.

The research is devoted to solving an important scientific problem, which is to develop a model of a reactive power compensator and its control system, and to study the efficiency of reactive power compensation in electrical complexes and electrical networks by computer simulation of its operation. The purpose of the paper is a

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model-based study to establish the means to improve electric power quality and power efficiency of autonomous electric power systems (AEPS), which consists in the development of a model of a static thyristor compensator and its automatic control system which would provide quick compensation of the reactive power and maintain a controlled parameter in accordance with the desired one. Additionally, the research of the characteristics of the higher harmonics active filter to reproduce the sinusoidal waveform of voltage in a three-phase network has been carried out.

To achieve the set purpose, the following objectives have to be solved:

1) Perform an analysis of methods for improving power efficiency and power quality in autonomous electric power systems, of reactive power compensation methods, and means of active filtering of the circuit voltage to restore its sinusoidal form.

2) Develop block diagrams of a static thyristor reactive power compensator and its microprocessor-based control system, to synthesize a dynamic model of an active filter in an analytical form. In this case, the converter should be addressed as a closed loop system in which precise compensation is performed by several control loops according to the principle of subordinate control.

3) Develop a MATLAB model of a static thyristor reactive power compensator and of an automatic control system which includes a thyristor control pulse shaping unit, a power measurement unit and a power quality specifications measurement unit to conduct model studies of its operation and the efficiency of the automatic control system.

4) Carry out simulation studies to obtain the oscillograms of voltage and current during the operation of the STC automatic control system, and the amplitude-frequency and phase-frequency characteristics of the active filter to specify the dependence of the filter smoothing coefficient on the cutoff frequency in the range of stable operation of the converter, to analyze the obtained results and to make conclusions.

The object of research is electromagnetic processes in an electrical complex with a reactive power compensator, which includes passive and active filters of higher harmonics in its structure. The subject of the research is the relationship, features, and peculiarities of the reactive power compensator usage in AEPS, as well as the control of electromagnetic processes in AEPS with a reactive power compensator. To solve the problems posed in the paper, the fundamental provisions of the theory of electrical circuits, mathematical and simulation modeling for calculating electromagnetic processes were used.

The modes of (AEPS) operation when the generator operates in parallel with the network, for example, cogeneration plants [10]. In such operating modes, it is necessary to solve the problem of maintaining the power coefficient optimal for the mode [11]. Moreover, the optimal management of reactive power flows also has a positive effect on the voltage stability in the network, as shown in [12]. However, reactive power generation can be carried out both by power plant generators and by specially installed compensating devices – reactive power sources, as shown in [13, 14]. This would, in turn, change cosφ power coefficient.

During the operation of the static thyristor compensator, higher harmonics are generated in the network, which degrade the voltage quality. Therefore, it is advisable to use an active filter to restore the voltage shape. Wang *et al*. [15] proposed a novel integrated method for harmonic suppression and reactive power compensation in distribution network, the idea of which is to dynamically monitor harmonics and power factor changes. However, this work does not present a mathematical description of the active filter and the structure of the model. In [16], a model predictive controller using shunt active power filter and a FACTS device like static VAR compensator was proposed to filter the harmonics of current and to reduce the impact of reactive power in transmission line in order to improve the power quality. The implementation of this method in Matlab is also considered. However, the analysis shows that the reactive compensator control system can be simplified and better adapted for implementation on the basis of microprocessor technology. At the same time, the option of joint use of passive and active filters to restore the voltage shape during the operation of a static thyristor compensator was not considered. A unified mathematical model of the power flow in a system containing a reactive component compensator consisting of capacitor banks connected in series to a thyristor control reactor was presented in [17]. At the same time, not enough attention has been paid to the issues of computer modeling of such systems and ways to improve the quality of the network voltage have not been considered. The main emphasis in this work is on the development of models of energy flows in the network and their analysis to justify the feasibility of using the FACTS device, on improvement of modes of functioning of the electric power system, but the structure of the control system is not considered.

To maintain a fixed power factor, it is necessary to develop an automatic control system with a compensating device that would maintain cosφ at a set level. The use of static thyristor compensators to reduce economic costs in the operation of industrial equipment was proven by the results of studies published in [18]. Serhii [19] studied STC with forced switching and insulated neutral, for which the integral indicators of its energy process and operating speed for two reactive power control strategies are specified. It is proposed to use the value of the specific consumed active power, which decreases due to an increase in the thyristor control angle, as a criterion for the economic efficiency of STC as a reactive power source. At the same time, no tools have been proposed, in particular no model the use of which would allow to specify the characteristics of the control strategy (thyristor control angles) in which the optimal power efficiency mode would be achieved. Onah *et al.* [20] proposed an improved circuit engineering solution for the STC based on a transformer type shunt-controlled reactor. The advantage of this solution is its high speed, unification of functions of the reactor and transformer, reactive power self-regulation provided by the capacitor section. However, the significant disadvantages of this solution include large internal losses of reactive power in STC networks with increased inductance while operating in the modes of its maximum output.

In [21], approaches were considered for controlling a hybrid VAR compensator, which consists in the use of passive and active parts. The passive part is represented by a thyristor-switched capacitor bank. The power part of the active part is implemented on the basis of an autonomous voltage inverter, connected through a voltage transformer in series with a passive part. But this work does not consider the possibility of using a hybrid active filter to improve the voltage quality, which, in turn, can also be hybrid and consist of passive and active filters connected in series. In [22–24], the techniques for solving the problem of reactive power compensation were also considered. But, on the one hand, they are applicable to wind farms or hybrid power plants, including wind turbines and diesel generators, and the power system itself is a power grid. At the same time, the control algorithms used, such as oppositional harmonic search, ant lion optimization, binary-coded genetic algorithm, and symbiosis organisms search, consider the specifics of the operating modes of such grid systems. That is, these works do not consider the use of static thyristor compensators, and, accordingly, their models, to solve the problem of reactive power compensation, but instead use static synchronous compensators multi-axis control with forced switching, which, as also indicated in [25], have a number of disadvantages, namely, low reliability and high cost. In [26], the solution to the problem of reactive power compensation in relation to a chemical plant was considered and is not universal. The calculation of the cost of using the installation for reactive power compensation is carried out, considering the daily consumption of electricity. In addition, this paper does not consider the issues of modeling the reactive power compensator control system and the use of an active filter to improve the quality of the voltage. In other words, the details of the implementation of such a system and the modeling of its operation are not touched upon.

A comparative study of two methods of static compensation (a switched thyristor capacitor and a thyristor commutated reactor) was accomplished in [27]. This paper also indicates that active power should be the main component of the power flow, while a reactive power should be supplied to the network in a sufficient and minimal amount. It becomes necessary to compensate the reactive power flow to ensure the stability and reliability of the power system. Therefore, it is necessary to further develop and improve STCs and their control systems.

In [28], a stationary modelling of both a static synchronous compensator (SSC) and a thyristor-controlled series compensator (TCSC) for power flow studies were presented. The SSC is modeled as a regulated voltage source with the resistance and operating angle consecutively. The model for TCSC is used to control an active power flow of the line on which the TCSC is installed. To test the effectiveness of the proposed models, the Newton-Raphson method algorithm was implemented to solve the power flow equations in the presence of SSC and TCSC. However, this approach requires significant computational costs to solve a set of equations represented in an analytical form. In addition, in order to demonstrate the performance of the proposed models, the authors of the said work conducted a study on a 9 bus bars system, which proves the effectiveness of the algorithm, but is of little practical use. In order to solve objectives of improving the electric power quality in AEPS, modeling with computational models is widely used. At present, it is impossible to create all-purpose AEPS [29] models which would adequately reflect their properties in different operation modes. Therefore, the studied objects are specialized mathematical models describing individual processes in AEPS. The effectiveness of various STC control methods can be studied on the basis of the model proposed in this work. In [30], the method of sub-synchronous resonance damping with thyristor-controlled was used for series compensators, and in [31], it was used for the purpose of improving the quality of the current in the "network-controlled bridge thyristor reactive power compensator" system. In order to obtain accurate static compensator model parameters and meet the increasingly complex power system modeling requirements, the work presented here proposes a model parameter identification method based on the chicken swarm optimization algorithm [32]. The MATLAB STC model proposed in this paper is quite universal and can also be used to study a modified thyristor reactor [33], the concept of control for which lies in changing the shape of the current by adding an auxiliary circuit and in the effect of changing the distributive network inductance on the modes and parameters of thyristor reactive power compensator equipment [34], which will allow to enhance the results obtained in the mentioned publications. Undoubtedly, the influence of reactive power compensators on the electrical network, considering the provisions discussed in [35], should be taken into account, and the use of active filters in such cases is appropriate and justified.

In works [36] and [37], methods and systems for reactive power compensation were considered in relation to high-voltage power lines, in which the voltage value is tens and hundreds of kilovolts. Based on the analysis of recent publications in the selected area of research, it can be argued that the issues of increasing energy efficiency by reactive power compensation, improving the quality of electricity are given great attention, and there are many individual solutions. Nevertheless, as noted by the authors of the considered publications, these issues remain relevant. There are reserves for improving systems and control algorithms for reactive power compensators. The use of a combination of an active and passive filter together with a reactive power compensator will improve the energy efficiency of AEPS.

It should be noted that the issue of improving electric power quality and power efficiency should be addressed comprehensively, with a system approach. The results of the study, given in this paper continues with and add to the studies aimed at improving the methods and technical means for upgrading electric power quality in an AEPS network [38] and increasing the power efficiency of the AEPS [39].

The contributions of this paper consist in solving the set scientific and practical problems, developing a simulation model and a mathematical description of the active filter, which is used when operating an electrical network with a reactive load and an installed reactive power compensator. Also, a structure for the system for the purpose of implementing control algorithms was developed. A simulation model of the proposed compensator as part of AEPS was developed and investigated. The effectiveness of the developed control algorithm was proved. As a result of the simulation, it was found that for a load with a power factor (cosφ) value between 0.5 and 0.6, it is possible to increase it and ensure operation with a power factor value that lies in the range from 0.8 to 0.95, and a THD of consumed current in the range 10% to 25%.

II. REACTIVE POWER COMPENSATION SYSTEM MODEL DEVELOPMENT

A Development of the Reactive Power Compensation System Block Diagrams

A reactive power compensation system usually consists of two subsystems: a static thyristor compensator power block unit and a microprocessor-based control system.

The operating principle of a microprocessor-based control system, the block diagram of which is present in Fig. 1, is to determine the angle of shift of the current in relation to voltage. The control system should generate control pulses of the thyristor-reactor group for the power section according to this angle and according to the control algorithm. The measured value of the shift between voltage and current in the network is transmitted to the microcontroller for further operation with these signals at the software level. The indication of the thyristors opening angle is performed by the software algorithm of the microcontroller.

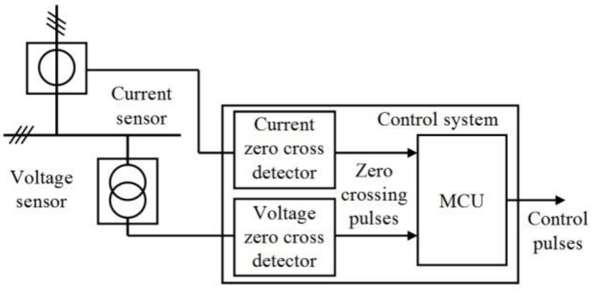

Fig. 1. Block diagram of the microprocessor-based control system.

The STC automatic control system has to ensure fast compensation of the reactive power and maintenance of the controlled parameter in accordance with the set setting, protect the STC equipment, and monitor/signal failures. The valve inverter control system should generally perform the following functions:

- Turn on the inverter and to set it to the specified mode.
- Stabilize the specified mode (voltage, current, power, frequency).
- Regulate the operating mode in accordance with the task.
- Protect and switch off the inverter.
- Control inverter operation and diagnose the faults.

These functions are implemented in the control system by changing the time of turning on and off the valves. This, in turn, puts three requirements on the control system:

1) Controllability of the duration of time for turning on/off the valves within the required limits. For the thyristor inverters with partial control and artificial switching (rectifiers, dependent inverters etc.), for the full control range theoretically, it is necessary to change the control angle α in the range 0° to 180° provided that the load is purely active (resistive). But in practice, the control range will be in the range of 0° to 180° – $\beta_{\min}$, which depends on the schematic and the nature of the load (active, active-inductive). For converters with full control and pulse-width methods of voltage regulation (i.e. direct-current voltage controllers, autonomous voltage inverters etc.), in accordance with their control characteristics, the full control range requires to change the width of the control pulses within the switching cycle 0 to T_s with a possible change of the period T_s itself.
2) Development of the control rectangular pulse with a steep leading edge and a set duration. A steep leading edge (usually one microsecond long) is necessary to indicate the turn-on time of valves that have a spread in turn-on ranges, as well as to reduce power losses in the valve during turn-on due to its final speed. The requirements for the duration of the control pulse depend on the type of valve and its mode of operation in the inverter.
3) Galvanic isolation or matching of voltage levels of a low-voltage control system, from the power circuit of the inverter, with a voltage level that is dangerous for a person or the control system itself.

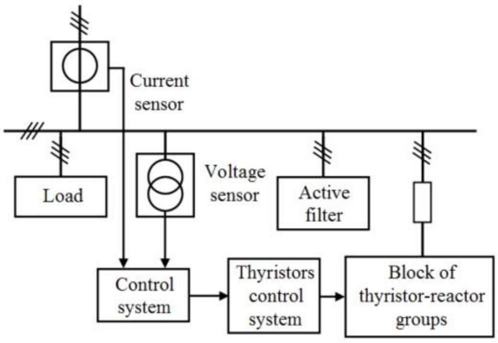

Fig. 2. Block diagram of a static thyristor compensator

STC main circuit configuration includes capacitor banks configured as higher harmonic filters, i.e., compensation filter circuits that are permanently connected to the network or can be commuted by switches and connected in parallel to them in a triangle of thyristor-controlled reactors, i.e. thyristor-reactor groups. The turn-on angle of the thyristors can quickly change so that the current in the reactor monitors the current voltage or reactive power in the electric power system. The STC automatic control system ensures fast compensation of the voltage reactive power and maintenance of the controlled parameter in accordance with the set setting.

B Development of an Active Filter Block Diagram and Synthesis of an Automatic Control System

An active filter, which is a static thyristor compensator shown in Fig. 2, is used as a compensation filter unit to restore the sinusoidal voltage in the network. The idea of using an active filter in order to generate interference in antiphase to the interference generated by the static thyristor compensator. A basic element of the active filter is a three-phase controlled semiconductor power converter. A simplified structure of the converter is present in Fig. 3.

As it can be seen in Fig. 3, a change in the effective value of the circuit voltage ΔU and the supply frequency Δf leads to a change in the output voltage U_{out}. The output voltage ripple can be represented as an additive obstacle Δu_p.

The value of the rectified voltage is affected by control voltage, effective mains voltage and mains frequency. With a significant asymmetry of the phases of the supply voltage, the output filter must be designed to suppress the first harmonic of the ripples, which has $f_1 = f_c$.

An increase in the amplitude of ripples in the output voltage of the converter is observed with an increase in the switching angle α. With an increase in the frequency of the supply network f_n and α =const, an increase in the amplitude of the ripples is observed. In the absence of asymmetry of the supply voltage, the main ripple frequency of the rectified voltage is $f_n = m\,f_c = 6\times 50 = 300$ Hz. In the presence of supply voltage asymmetry, the output voltage ripple frequency is $f_n = f_c = 50$ Hz.

To effectively eliminate ripples in the rectified voltage, an active filter can be used. Its general scheme can be seen in Fig. 4.

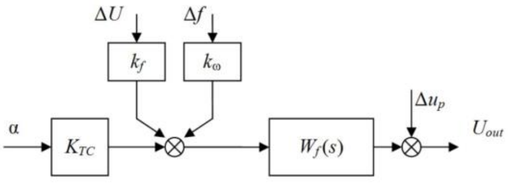

Fig. 3. Converter simplified structure.

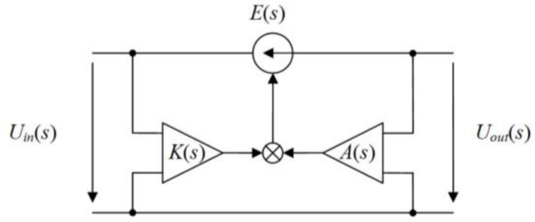

Fig. 4. Active filter general scheme.

In order to find the transfer function of the active filter $W_{\text{af}}(s)$ is to be found, using Kirchhoff's second law:

$$U_{\text{in}}(s) = E(s) + U_{\text{out}}(s)\ . \tag{1}$$

In turn, the EPC $E(s)$ is equal to:

$$E(s) = U_{\text{in}}(s)K(s) + U_{\text{out}}A(s)\ . \tag{2}$$

Substituting (2) into (1)

$$W_{\text{af}}(s) = \frac{U_{\text{out}}(s)}{U_{\text{in}}(s)} = \frac{1-K(s)}{1+A(s)}\ . \tag{3}$$

If by input voltage we mean the ripple voltage ($U_{\text{in}}=U_p$), then eliminating the ripples will require that $U_{\text{out}}=0$, which results in:

$$W_{\text{af}}(s) \to 0\ . \tag{4}$$

Equation (4) will be fulfilled if

$$K(s) \to 1,\ A(s) \to \infty\ . \tag{5}$$

A series connection of two filters is to be considered (Fig. 5).

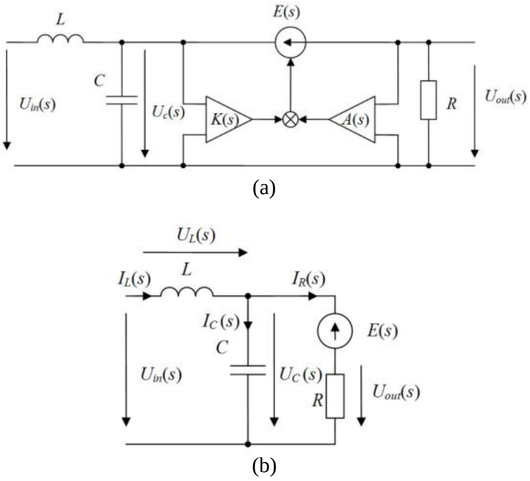

Fig. 5. Serial connection of *LC* filter, active filter and voltage: (a) block diagram and (b) design diagram.

For Fig. 5(b), an equation according to the Kirchhoff's laws can be drawn up:

$$\begin{cases} U_{\text{in}}(s) = U_L(s) + U_C(s) \\ U_{\text{in}}(s) = U_L(s) + E(s) + U_{\text{out}}(s) \cdot \\ i_L(s) = i_C(s) + i_R(s) \end{cases} \tag{6}$$

The currents $i_L(s)$, $i_C(s)$, $i_R(s)$ are described by the expressions:

$$i_L(s) = \frac{U_L(s)}{sL}\ , \tag{7}$$

$$i_C(s) = sCU_C(s)\ , \tag{8}$$

$$i_R(s) = \frac{U_{\text{out}}(s)}{R}\ . \tag{9}$$

Eqs. (8) and (9) is to be substituted into the third equation of the system (6):

$$i_L(s) = sCU_C(s) + \frac{U_{\text{out}}(s)}{R}. \qquad (10)$$

Using Eqs. (10) and (7), the voltage drop across the inductance can be found:

$$U_L(s) = sL\left[sCU_C(s) + \frac{U_{\text{out}}(s)}{R}\right]. \qquad (11)$$

Eq. (11) is to be substituted into the first equation of the system (6) and $U_C(s)$ can be expressed:

$$U_C(s) = \frac{U_{\text{in}}(s) - \frac{sL}{R}U_{\text{out}}(s)}{1 + s^2LC}. \qquad (12)$$

An input voltage for the active filter is the voltage of the capacitor $U_C(s)$, therefore, using Eq. (3), we can write:

$$U_C(s)[1 - K(s)] = [1 + A(s)]U_{out}(s). \qquad (13)$$

Substituting (12) into (13) we get:

$$W(s) = \frac{U_{\text{out}}(s)}{U_{\text{in}}(s)} = \frac{1}{\frac{1+A(s)}{1-K(s)}s^2LC + s\frac{L}{R} + \frac{1+A(s)}{1-K(s)}}. \qquad (14)$$

Eq. (14) can be rewritten as:

$$W(s) = \frac{W_{\text{af}}(s)}{\left[LCs^2 + W_{\text{af}}(s)\frac{L}{R}s + 1\right]}. \qquad (15)$$

The resulting quadratic equation is:

$$LCs^2 + W_{\text{af}}\frac{L}{R}s + 1 = 0. \qquad (16)$$

In order for the roots of the (16) not to be complex conjugate, it is necessary to fulfill the condition:

$$\left(W_{\text{af}}\frac{L}{R}\right)^2 - 4LC > 0. \qquad (17)$$

Therefore

$$W_{\text{af}} > 2R\sqrt{\frac{C}{L}}. \qquad (18)$$

Fig. 6 is a practical diagram of an active filter. To cut off the constant component in the diagram, there are *RC* circuits, i.e., high-pass filters.

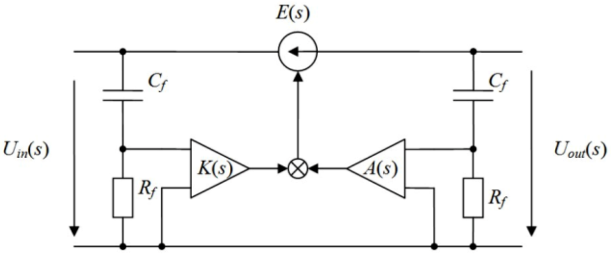

Fig. 6. Active filter practical diagram.

The high-pass filter, consisting of R_f and C_f, has a transfer function:

$$W_{\text{RC}}(s) = \frac{R_f C_f s}{1 + R_f C_f s}. \qquad (19)$$

Then the active filter transfer function in Fig. 6 shall look like:

$$W_{\text{af}}(s) = \frac{U_{\text{out}}(s)}{U_{\text{in}}(s)} = \frac{1 - W_{\text{RC}}(s)K(s)}{1 + W_{\text{RC}}(s)A(s)}. \qquad (20)$$

To build a closed structure converter (Fig. 7) we will use the block diagram present in Fig. 3. The link with the transfer function $W_f(s)$ is described by (14). To eliminate output voltage ripple, the cutoff frequency $W_f(s)$ must be kept to a minimum.

To improve the system operating speed, circuit to compensate for external disturbances ΔU and Δf can be used (colored gray in the diagram). This circuit provides imprecise compensation. It does not affect the stability of the system.

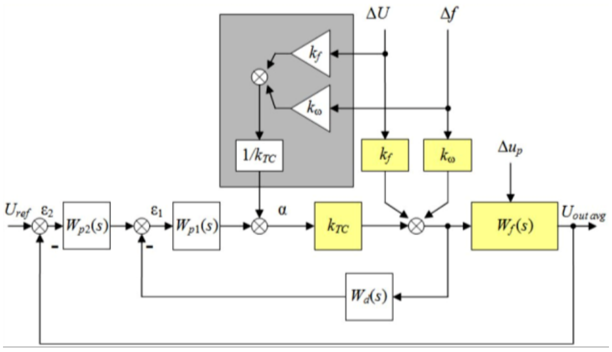

Fig. 7. Structural diagram of the converter as of a closed system.

Precise compensation is carried out by two control loops on the principle of subordinate control. The internal circuit is designed to adjust the average value of the rectified voltage. An aperiodic link with a transfer function can be used as $W_d(s)$:

$$W_d(s) = \frac{1}{\tau s + 1}, \qquad (21)$$

where τ is the time constant of the medium voltage sensor (0.01s to 0.05s). The $W_{p1}(s)$ controller can be proportional. The external control loop for voltage static error elimination must include a proportional-integral controller $W_{p2}(s)$.

C Static Thyristor Reactive Power Compensator Model Development

To study the processes occurring in the network after the moment of reactive power compensation under different conditions, the model developed in the MATLAB package, as presented in Fig. 8.

The formation of the corresponding opening angle of the thyristors α, at which reactive power is compensated, is carried out using the automatic control system (ACS). In Fig. 8 this unit is marked as SAU. Its block diagram is presented in Fig. 9.

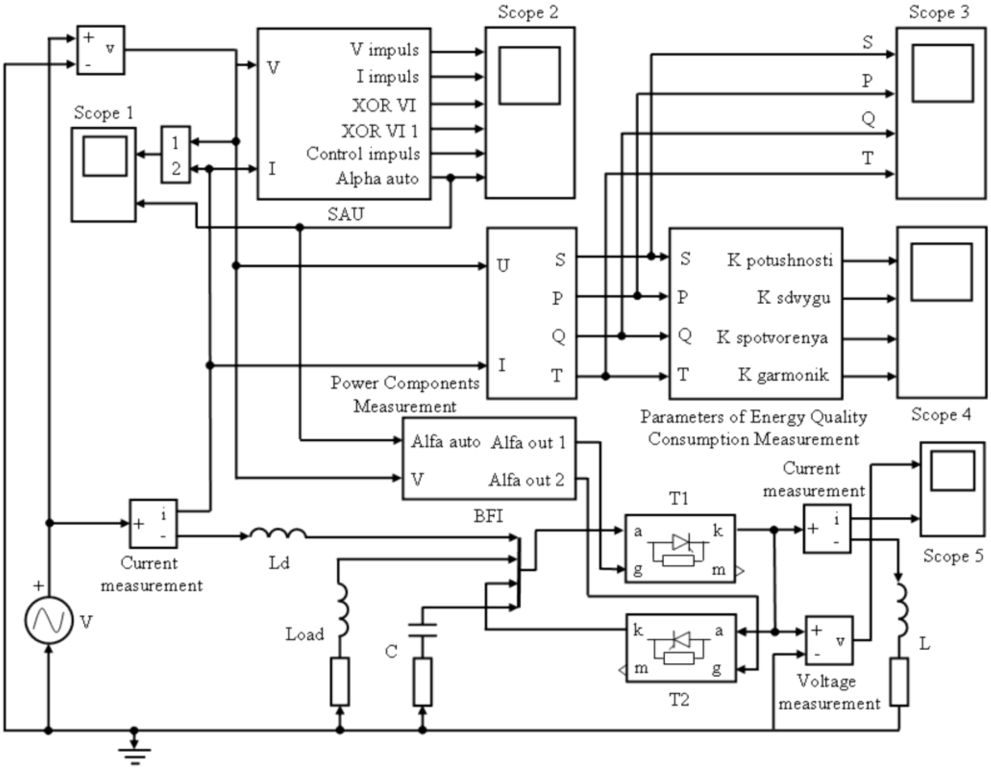

Fig. 8. General outline of the studied reactive power compensator model.

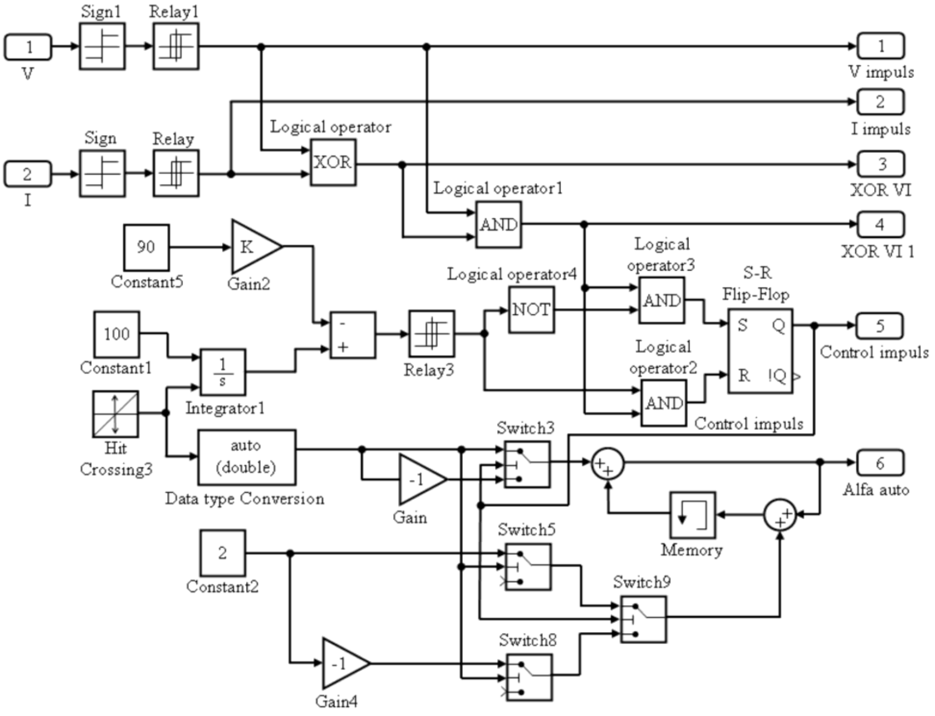

Fig. 9. Block diagram of the automatic control system unit (SAU).

The unit’s operating principle is as follows. First, sinusoidal voltage and current signals are indicated in the network. Further, by means of the Sign and Relay blocks connected in series, they are converted into a rectangular shape and transmitted to XOR Logical Operator unit (exclusive OR element). At its output, pulses of the divergence between voltage and current will be observed each time the signal passes through zero. After that, a system was created using elemental logic. It generates a control pulse for a counter device built on the basis of an adder and a memory unit. Provided that if the current outpaces the voltage, then the counter increases by 4°, and if the voltage outpaces the current, then the counter decreases by 4°. The 4° angle was found experimentally by finding the optimal speed/distortion ratio. The effective voltage value in the model is 220 V (amplitude voltage is 311 V).

With sinusoidal supply voltage

$$U(\theta) = U_m \sin(\theta) ,$$

and symmetrical control of thyristors, at the moment (θ = α) the control pulse is applied to the first thyristor, current will flow through it.

$$i_1(\theta) = \frac{U_m}{X\sqrt{1+\rho^2}}(-\sin(\alpha-\varphi)+\sin(\theta-\varphi)),$$

where $\varphi = \mathrm{arctg}(1/\rho)$, $\rho = R/X_L$, $X_L = \omega L$, $\theta = \omega t$.

Equating the right side to zero, we get the turn-off angle of the first thyristor:

$$\alpha_{sw1} = \pi + 2\varphi - \alpha .$$

During the action of the negative half-wave of the supply voltage, when a control pulse is applied at the moment $\theta = \pi + \alpha$, the second thyristor opens. At the moment the current of the second thyristor passes through zero, this thyristor closes. The processes occurring in the circuit of the second thyristor are identical to the processes in the circuit of the first thyristor through the symmetry of the supply voltage. Therefore, there is no need to determine the current through the second thyristor and its turn-off angle. In this case, it is enough to find the integral indicators of the energy process in the STC and double the result.

The power consumed by reactors in a three-phase circuit is also a function of the thyristor control angle and is given by:

$$Q_L = 3U_{\mathrm{ph}}^2\left[1 - 2\alpha/\pi - \sin(2\alpha/\pi)\right]/X_L ,$$

where U_{ph} is the effective value of the phase voltage of the network.

The total power of the STC can be determined by the equation:

$$Q_{\mathrm{STC}} = 3U_{\mathrm{ph}}^2/X_C - 3U_{\mathrm{ph}}^2(1 - 2\alpha/\pi - \sin(2\alpha/\pi))/X_L ,$$

Since the thyristors are connected in antiparallel, the control of one thyristor must be carried out in antiphase to another and vice versa. Strict synchronization with the circuit voltage is also required. These functions are performed by the thyristor control pulse shaping unit (BFI), as shown in Fig. 10.

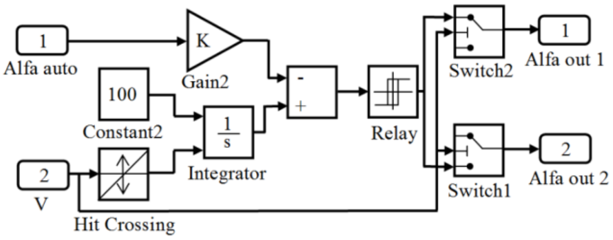

Fig. 10. Thyristor control pulse shaping unit (BFI).

It is known that the instantaneous power of all energy subsystems of various electrical complexes, including AEPS, is determined by the product of the instantaneous values of voltage and current at their input [3]. It is equal to the rate of arrival of electromagnetic energy at this moment in time and, in the general case, changes during the period of alternating current in amplitude and sign. The active power P is equal to the average value of the instantaneous power over the supply voltage period and determines the amount of electromagnetic energy converted into other forms of energy. It characterizes the useful work in the load, including the useful power and power losses in the installation. The total power S is always greater than the active power transmitted to the load due to the existence of inactive power components, which, without creating a useful effect, lead to an increase in losses in the power supply network. Three inactive components of total power are known: reactive power or shear power, distortion power and unbalance power. Reactive power or shift power Q occurs due to the phase shift of the fundamental harmonic of the current relative to the mains voltage. As a result of the displacement of the main current harmonic, a reactive current component appears, which does not participate in the transfer of active power to the load, since the average value of the instantaneous power over the period due to this current component is zero. The distortion power T occurs due to the higher current harmonics. The average value of the instantaneous power associated with these harmonics is zero over the period, however, they also cause additional energy losses in the network. The unbalance power H considers the additional energy losses associated with the uneven distribution of current over the phases. In single-phase and multi-phase symmetrical converters, the unbalance power is zero.

A special active and reactive power unit, included in the sim power systems\extra library\measurements library, allows to determine the active power P and reactive power Q in the energy subsystem. For the case of powering energy subsystems from a single-phase network, a power components measurement block was developed, made in the form of a subsystem (Fig. 11), which makes it possible to determine S and T through known ratios:

$$S = U_{\mathrm{RMS}} I_{\mathrm{RMS}} = \sqrt{P^2 + Q^2 + T^2} , \tag{22}$$

$$T = \sqrt{S^2 - (P^2 + Q^2)} . \tag{23}$$

where U_{RMS}, I_{RMS} are the effective values of the voltage and current of the primary power source.

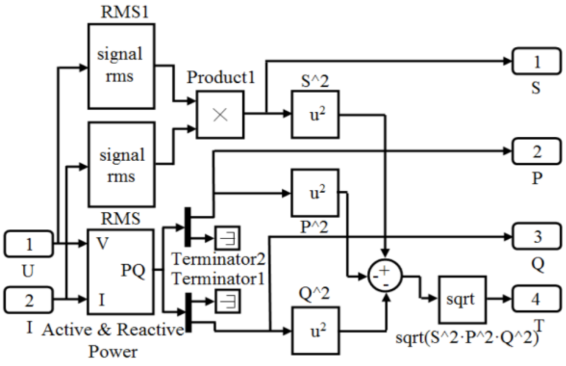

Fig. 11. Power components measurement power measurement unit.

After gross power S of the energy subsystem and its components P, Q and T are found, it is possible to determine the main indicators of energy consumption quality: K_{power} – power factor, K_{shift} – shift factor, K_{dist} – distortion factor, K_{THD} – total harmonic distortion factor.

The power factor of an electrical complex characterizes the ability of this complex to consume electrical energy from the primary power source [3]:

$$K_{\text{power}} = \frac{P}{S}\,.$$

The shift factor characterizes the energy exchange between the receiver and the source, due to the ability of the reactive elements of the electrical complex to accumulate and release energy [3]:

$$K_{\text{shift}} = \frac{P}{\sqrt{P^2 + Q^2}}\,.$$

The distortion factor characterizes the energy exchange between the source and the receiver, due to the higher harmonic components of the current [3]:

$$K_{\text{dist}} = \frac{\sqrt{P^2 + Q^2}}{\sqrt{P^2 + Q^2 + T^2}}\,.$$

The harmonic factor, or the integral indicator of the harmonic composition of the current, characterizes the ratio between the energy due to the higher harmonics of the current and the energy due to the fundamental (first) harmonic [3]:

$$K_{\text{THD}} = \frac{\sqrt{\sum_{k=2}^{N} (I_{k\text{RMS}})^2}}{I_{1\text{RMS}}}\,.$$

Fig. 12 presents the developed parameters of quality of energy consumption measurement unit designed as a subsystem that calculates energy consumption quality indicators from known values of S, P, Q, and T.

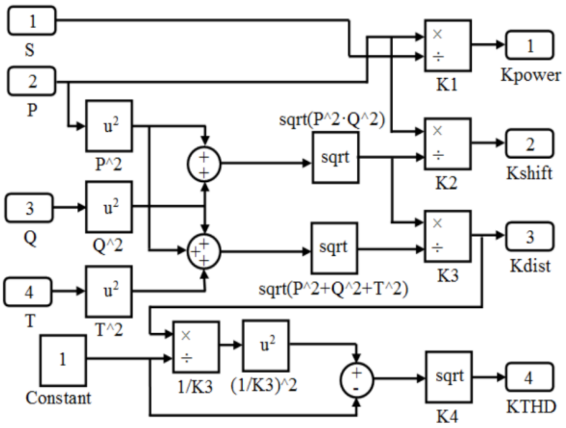

Fig. 12. Parameters of quality of energy consumption measurement power consumption quality specifications measurement unit.

Prior to the study of reactive power compensator automatic control system operation, a model experiment was carried out, in which the range of the input parameter α changed from 0° to 180° within a second. Fig. 13 represents oscillograms for voltage and current during ACS unit operation. According to the results of the experiment, it was found that the full compensation of the reactive current occurs at 0.64 s, with the switching angle at about 116°. Due to the increased switching angle, value of the current in the reactor smoothly decreases and significant distortion of the voltage supplied to it can be seen in Fig. 13. Then another experiment was carried out, when an automatic control system (ACS) was turned on.

As can be seen from Fig. 13, the developed control system expands the switching angle automatically by the set value as long as the current exceeds the voltage (which indicates the capacitive nature of the voltage) and reduces it by the same value as long as the voltage exceeds the current. It should be noted that it is usually not recommended to fully compensate for the reactive power (up to $\cos\varphi = 1$), since overcompensation is possible (due to the variable value of the active power of the load and other random factors). Usually, the value of $\cos\varphi = 0.90$–0.95 is acceptable.

The shape of the power supply main specifications during ACS operation is shown in Fig. 14.

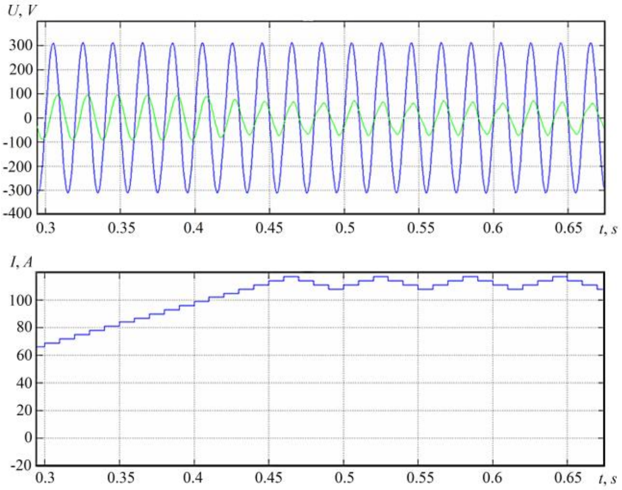

Fig. 13. Oscillograms for voltage and current during ACS unit operation.

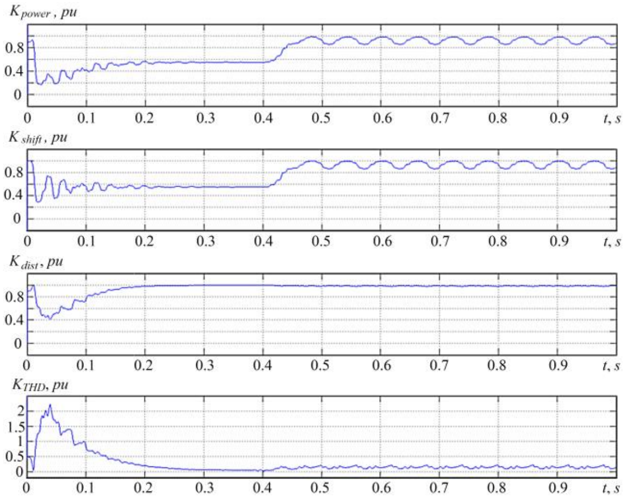

Fig. 14. The shape of the power supply main specifications during ACS operation.

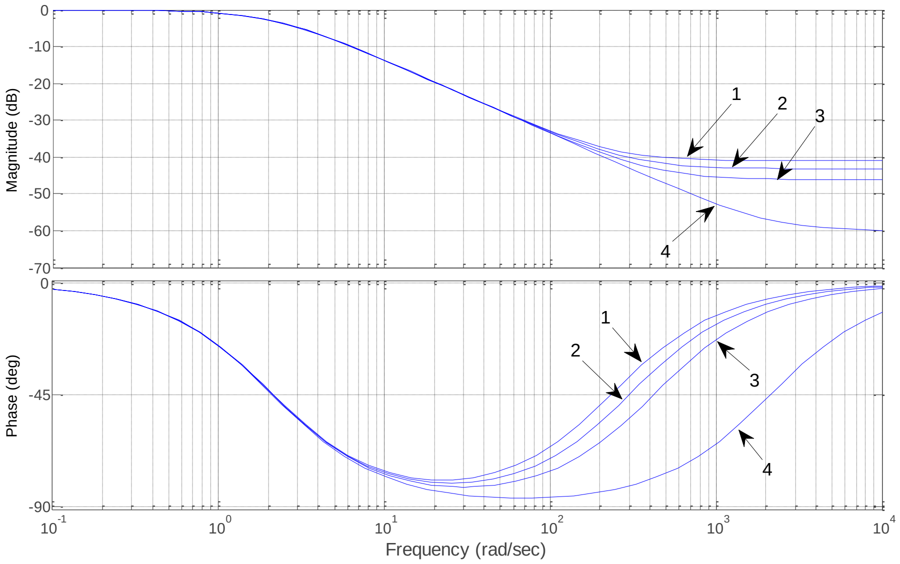

Fig. 15. Active filter frequency characteristics 1: $K(s)$=0.1, 2: $K(s)$=0.3, 3: $K(s)$=0.5, 4: $K(s)$=0.9.

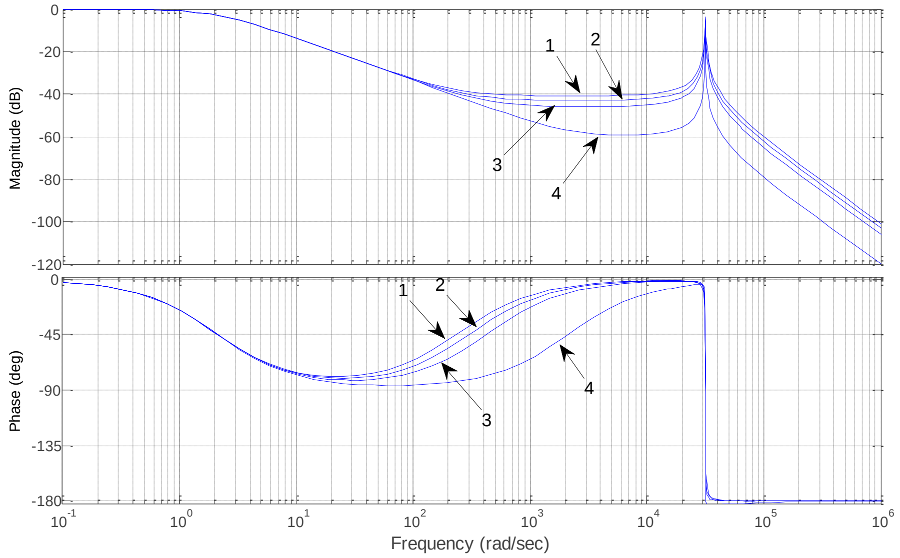

Fig. 16. Cascade connection frequency characteristics of LC- and active filters 1: $K(s)$=0.1, 2: $K(s)$=0.3, 3: $K(s)$=0.5, 4: $K(s)$=0.9.

Fig. 15 shows a set of active filter frequency characteristics and Fig. 16 shows the frequency characteristics of the cascade connection of an *LC* filter and an active filter, which are obtained for different values of $K(s)$.

The numerical values of the passive and active filter elements for which the measured characteristics were obtained are as follows: L=1 mH, R_f=100 Ohm, C_f=47 uF, $A(s)$=100, C=1 μF, R=20 Ohm. In this case, the value of the coefficient $K(s)$ (Eq. (3)) was varied. Wherein with an increase in the inductance L of the filter, the resonant frequency shifts to the low-frequency region.

Analyzing the graphs, we come to the conclusion that as the gain factor $A(s)$ increases, the cutoff frequency of the filters shifts to the lower frequencies. At the same time, the effective time constant increases, which affects the transient characteristic.

The influence of the factor $K(s)$ on active filter frequency characteristics are presented in Fig. 15, and on the cascade connection frequency characteristics of the *LC* filter and active filters are presented in Fig. 16. As it can be seen, an increase in the ripples amplitude of the converter output voltage is observed with an increase in the turn-on angle α. With an increase in the network supply frequency f_{net} and a constant α, an increase in the amplitude of the ripples is observed. The external interference (splashes and dips in the supply voltage and changes in the frequency of the supply network) compensation channel allows to significantly improve the dynamic properties of the converter. A means for effectively eliminating rectified voltage ripple is the cascade connection of an *LC* and an active filter. According to the amplitude-frequency characteristics of the filter obtained as a result of modeling, it can be seen that it effectively attenuates harmonics from 4 to 50 by 40 dB. At the same time, with an increase in $K(s)$, the attenuation of harmonics by the filter can reach 60 dB. Reducing the active filter cutoff frequency leads to an increase of the effective time constant, which affects the operating speed of the entire system. To eliminate this shortcoming, the control system can be built on the principle of subordinate regulation.

III. CONCLUSION

Based on the literature review and performed analysis on methods for improving power efficiency and power quality in AEPS, it became clear that there are reserves for further improvement of AEPS energy efficiency and power quality and this issue needs to be approached comprehensively and systematically.

The method of providing smooth control of the reactive power of a static thyristor reactive power compensator, which includes a series-connected active and passive parts, has been further developed. The control system of the active part of the reactive power compensator has been improved, which ensures the formation of a sinusoidal current in the capacitors of the passive part of the compensator, which makes it possible to eliminate overvoltage on them and improve the reliability of the compensator. A simulation model of a reactive power compensator and its control system has been developed, a mathematical description of their operation has been made, which makes it possible to analyze the operation of a compensator when connected to a network, with or without non-sinusoidal and asymmetry.

Block diagrams of a reactive power STC and its microprocessor-based control system have been developed, a model of an active filter based on a thyristor converter has been synthesized. The converter was addressed as a closed loop system in which precise compensation is performed by several control loops on the principle of subordinate control. The greatest interference suppression effect is observed if a second-order astatic controller is used. A feature of the STC control system is that, depending on the measured phase difference between current and voltage, the thyristor control angle changes continuously so as to reduce this phase difference to 0°, thereby providing full reactive power compensation. The phase difference signal between current and voltage is obtained with a zero cross detector and a logic circuit, and the signal itself is a PWM with a period equal to the period of the mains voltage. This signal impacts on the change of the thyristor control angle in the direction of increase or decrease, depending on the load (inductive or capacitive). Switching the sign of the direction of the increment of the thyristor control angle occurs synchronously with the change in the sign of the phase difference between current and voltage, therefore, in this case, the relay control principle is used. It is shown that with such a control principle, stable oscillations of the controlled parameter appear, the amplitude and period of which depend on the chosen increment step of the thyristor control angle (in the considered model this value is 4°). Reducing the increment step of the control angle of the thyristors will lead to a decrease in the amplitude of oscillations, but at the same time, the system performance will decrease.

Simulation results have shown that the use of a static reactive power compensator in conjunction with a higher harmonic passive and active filters is an effective way to improve AEPS power efficiency. Simulation of the system showed that for a load with a power factor of 0.5–0.6, it is possible to ensure operation with a power factor of 0.8–0.95 with a THD of consumed current in the range of 10%–25%. It was found that the shift of the logarithmic amplitude frequency characteristic controller cutoff frequency to higher frequencies within the range of stable operation of the converter leads to an increase in the interference smoothing coefficient. This feature is typical for all types of regulators, therefore, for the precise structures, controllers' parameters and type should be chosen based on a set of requirements based upon by both necessary static and dynamic indicators.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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