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THE USE OF THE POWER TRANSFORMERS FOR THE REGULATION OF THE POWER SYSTEM OPERATION

221.01 – POWER SYSTEMS AND TECHNOLOGIES

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The text of the thesis and the author's abstract can be found in the library of the Technical University of Moldova and on the website C.N.A.A. (www.cnaa.md).

The abstract was sent .

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CONCEPTUAL PROVISIONS OF THE RESEARCH

Urgency and Importance

In conditions of liberalization and reformation of the electric power industry in the power systems of various countries, the requirements are enhanced for the controllability improvement of the electric circuits. In this context, the FACTS (in particular, the PST) facilities are most extensively used at present.

Phase-shifting transformers that are controlled by the power electronic means are nowadays the major elements of the joined energy systems, which allow the SMART GRID technologies to be realized. The PST is found to be both an independent application (e.g., as a control by the power flows in closed non-uniform electric power lines) and a composite element of new combined FACTS-controllers on their base.

The development objective and study of the new technical solutions in this area of research is urgent and important both from the viewpoint of optimization of the PST parameters and increase in efficiency, flexibility and reliability of operation of modern electric power systems.

Major targets of research

- The analysis of the development tendencies of the means of control by the power system modes.
- The elaboration of the PST schematic variants and study of their mode parameters based on mathematic and structural-simulation modeling.
- Developing the means and algorithms of control by the angle of the PST phase-shifting.
- The research and analysis of the methods for reducing the standard power of the transformer devices.
- The comparative analysis of power characteristics of the objectives under consideration.
- The development and research of new combined FACTS-controllers based on the PST as the control element.
- The development of technical solutions, which ensure the improvement of quality of frequency transformation and transmitted power.
- The elaboration, manufacturing and testing of the PST physical model.
- The proposal development for the application of the facilities offered.

Scientific novelty of this work consists of the development and research of seven variants of phase-shifting transformers, which were not described earlier, with one of them being patented.

For the variants considered, the structural-simulation models were constructed. The latter allowed series of virtual experiments to be performed and the objectives in different modes to be studied (supported by 7 publications). The original mathematic models were developed using three of the schematic variants presented.

The PST-based FACTS-controllers schemes were developed and studied. On the basis of a triangle scheme, a frequency converter was proposed and studied in different modifications of a two-channel variant. An opportunity for a qualitative frequency transformation and active power transmission among the power systems with different standards to maintain the frequency was exhibited. Based on a multangular scheme, a controlled compensating device with a wide range of the reactive power regulation, both in the capacitive and inductive ranges was offered (supported by 8 publications).

Segmentation methods for the PST windings were proposed to ensure various discretion of regulation the phase-shift angle.

The methods for the improvement of the power transmission quality during the frequency conversion were offered (the use of the two-channel scheme, of additional inductive elements, and correction of the control strategy (a reverseless version)).

On the basis of the PST hexagonal configuration, the architecture of a physical laboratory model was developed.

Theoretical and practical merits of the research results.

The theoretical merit of the research consists in the elaboration of seven original schematic variants of phase-shifting transformers and two FACTS based on those transformers, for which mathematical, structural and physical models were constructed and tested. The calculation and natural experiments confirmed the methods and models used to be correct.

The research results are assumed to enrich the database of the theoretical knowledge of the branch. This will positively affect the advance of the practical innovations in enhancing the controllability of the electric power systems. The results of this work will serve as the stimulus for the theoretic investigations in the elaboration, manufacturing and application of the FACTS-controllers regulated using the power electronics, as the basis for the intellectual actively-adaptive networks. The research materials can serve as well as the basis for the development and design of controlling means by the modes of intersystems (interstates) connections to solve the problems of diversification in the electric power supplies and liberalization of the energy market in Moldova Republic.

Techniques and research methods

In order to create the operating models of the research objectives, obtainment and processing the results of the calculation experiments the methods of mathematic , structural, simulation and physical modeling were used, along with the research methods, such as measurement, comparison, analysis and synthesis. As the basis for modeling, computer modern technologies were used.

The dissertation major concepts to be defensed:

1. The PST schematic variants that allow reducing significantly the established (standard) power compared to classic schemes (patent).
2. Methods for sectioning the control windings and commutation laws by means of the power electronics for the purpose of realization of the required strategies of regulation.
3. Mathematic, structural-simulation and physical models of the PST for the purpose of the process investigation during the commutator control based on the elaborated strategies of regulation.
4. Schematic variants of the FACTS-controllers that ensure a controlled connection between the power systems with different frequency standards regulated by the PST.
5. Methods for quality improvement of the electric power transmission in the process of the frequency conversion (application of a two-channel scheme, the use of additional inductive elements, and correction of the control strategy (a reverseless version)).
6. The FACTS-controller schematic variant as a compensation facility with a wide range of regulation, both of a capacitive and inductive character, controlled using the PST.
7. Physical laboratory PST model with a control system.

Authenticity degree and approval of the results

The authenticity of the results obtained is supported by the use of the classic theory of the electric circuits, mathematic modeling, structural-simulation (Matlab) and physical modeling, as well as by the comparison of the results obtained using various methods of investigation.

Major points and results of the dissertation were reported and discussed at

1. The meetings and scientific-technical seminars at the Moldova Technical University.

2. FOREN 2014 - The 12th Wec Central & Eastern Europe Regional Energy Forum. key issue integrating renewable energy sourses into the electrisity transmission grid. Bucureşti, 21-26 iunie 2014.

3. SIELMEN 2015 10th International Conference and Exhibition on Electromechanical and Power Systems.

4. WEC Central and Eastern Europe Regional Energy Forum FOREN 201612-16 June 2016, Vox Maris Grand Resort, Costinesti, Romania.

5. International Conference "Energy of Moldova – 2016. Regional Aspects of Development" 29 September – 01 October, 2016 - Chisinau, Republic of Moldova.

6. Conferinţa a studenţilor, masteranzilor şi doctoranzilor (Universitatea Academiei de Ştiinţe a Moldovei) 15 Iunie 2017, Chişinău, Moldova.

7. Conferinţa tehnico-ştiinţifică a studenţilor, masteranzilor şi doctoranzilor (Universitatea Tehnică a Moldovei) 28.Martie 2019, Chişinău, Moldova.

8. 8th International Conference on Modern Power Systems (MPS), 21-23 May 2019, Cluj-Napoca, Romania

9. IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), 29 September to 2 October 2019, Bucharest, Romania

10. WEC CENTRAL & EASTERN EUROPE ENERGY FORUM – FOREN 2020, Energy Transition in South East Europe: Opportunities, Challenges, Perspectives Costineşti, Romania, 7-10 September 2020

On the topic of the dissertation, 1 patent was received; 11 articles were published (6 of them – in the THOMSON and 2 in SCOPUS databasis, 1 paper is with one author), and reports were presented at 6 international conferences.

Dissertation structure and volume

The work consists of introduction, five chapters, conclusions, references including 168 sources and 7 appendices, 190 pages of the main text, 15 tables and 117 figures. Based on the research results, 18 scientific papers are published.

Keywords: phase-regulation transformer, mathematic modeling, structural-simulation modeling, strategy of control, power characteristics, combined FACTS, laboratory sample.

BASIC CONTENT OF THE WORK

The introduction justifies the topic urgency of the dissertation work; the targets are formulated; the scientific novelty is discussed, and the practical merits are indicated along with the concepts to be defensed; the information on the approval and publication of the main research results is presented; and the structure and scope of the work are indicated.

Chapter 1, ‘PHASE-REGULATION DEVICES AS THE ELEMENT FOR REGULATION THE MODES OF MODERN POWER NETWORKS’, presents the characteristic of the phase-shifting transformer; the distinguishing features of the devices like these are described, i.e, their big sizes; enhanced standard power of the device that in a classical variant reaches 2.15 vs transient; a high cost (2-5$/кVA); and application exclusively for the purposes that make amendments for the manufacturing expenses.

It is shown that, using the phase-shifting transformers, the following problems can be tackled, namely, optimizing the normal mode of the electrical networks; melting ice on the wires of airlines; using the PST in the Assisted PST system; using the PST in the IPC (Interphase Power Controller) system; the transient modes control to enhance stability; removal the restrictions in the postfault and repair modes; improvement of the characteristics and increase in the power reserve of the substations; and modes regulation in the intersystem and interstate connections.

The chapter presents and studies the methods for generation of the additional voltage, which are used further on for the elaboration of the PST schematic variants, including transversal, longitudinal-transversal and symmetrical control.

Typical configurations (one- and two-transformer) were also described and the PST schematic variants (symmetrical and asymmetrical) depending on the nominal voltage, output power and the phase-shift angle, whose value affects directly the power and size of a transformer device.

The PST important element is the device, which controls a phase-shift angle. The PST regulatory means can be based on the electromechanical switches, or using the power electronics. The PST controlled by the use of the LTC (Load Tap Changer) mechanical devices cannot operate rapidly enough, since a switching process of just a single stage of control takes up to 5.4 s. A fast-reaction PST systems regulated by the power electronic means make it possible to be smoothly fit to the routine of the EES, ensuring its stability during the transient processes with optimal parameters.

One constraining factor of the PST application is a fairly high cost of the power semiconductor elements, which necessitates limitation of the functional properties of the control means by using a minimal amount of the necessary operations thus impairing the potentially existing possibilities. Cost cutting by reducing the PST typical power, can be used to expand its control functions at the expense of a more available application of the power electronic commutators.

The world practice was analyzed in the areas of development, manufacturing and implementation of the PST devices. The growth prospects of the world market of the phase-shifting transformers were estimated. It is shown that in the nearest future the growth dynamics will be around 6.8% and will reach as much as 100 mln. USD doll. by 2030 compared to 73 mln. USD doll. in 2019. The references review is performed according to the topic under study.

Chapter 2, 'MODELING THE CHARACTERISTICS OF THE PHASE-SHIFTING DEVICES', describes the methods and means used in the work for the purpose of reaching the goals set. The process of the research is based on the methods of mathematic, structural, simulation and physical modeling. The electric circuits theory was used as the basis for creation of the mathematic models. For the structural-simulation modeling, the MatLab–Simulink–SimPowerSystems were applied. For the physical modeling, the methods of study such as experiment, comparison, measurement, analysis and synthesis were made use of.

Three new PST schematic variants were proposed with a range of the angle regulation of $\psi = 0 \div \pm 60^{\circ}$: 'single-transformer with a regulation in a neutral point' (Fig. 1), 'triangle' (Figs. 5, 6), and 'star' (Fig. 8). The mathematic models were constructed for each of the PST, which determined the ratios between the mode parameters.

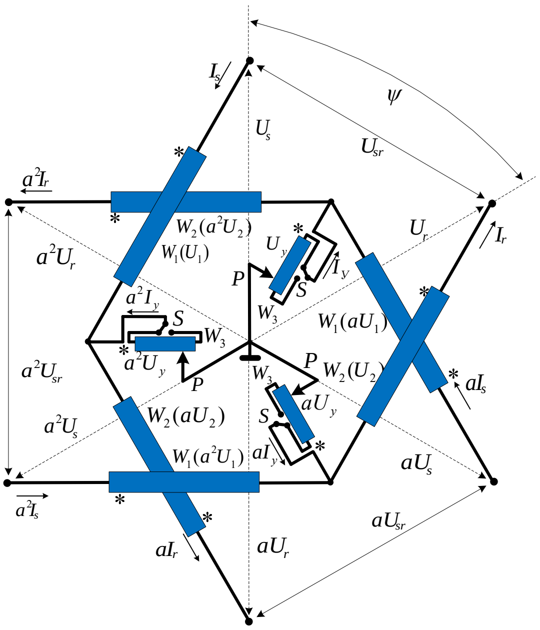

Fig.1. PST plotted according to a single-transformer scheme with regulation in neutral

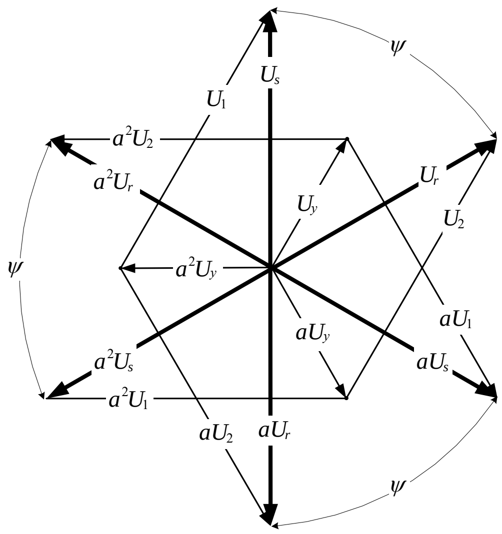

Fig. 2. Vector diagram of voltages

The device (Fig. 1) is a three-phase three-winding transformer composed of a three-phase systems of primary (W_1) and secondary (W_2) windings, as well as a three-phase system of control windings (W_3) with the regulation taps. Additional switch S sets up a regulation sign of a phase shift. The vector diagram of voltages, which illustrates the operation of the device (Fig. 2) allows obtaining the major expressions that characterize the device mode parameters.

In order to correlate the mode with a real state of the device the coefficient of control concept $k_y = \frac{W_3}{W_1} = \frac{W_3}{W_2}$ is introduced, which is an independent coordinate of regulation. The voltage complex transformation coefficient is determined from the expressions for the voltages at the device busbars:

$$U_s = U_1 + a^2 U_y = (1 + a^2 k_y)U,\ U_r = U_2 + a\ U_y = (1 + a\ k_y)U\ ,$$

where a is the complex operator of the three-phase system. Then $U_r = \frac{1 + a\ k_y}{1 + a^2 k_y} U_s$. The multiplier before voltage U_s, is its complex voltage transformation coefficient: $\dot{K} = \frac{1 + a\ k_y}{1 + a^2 k_y}$.

At $k_y = 0$ we obtain $\dot{K} = 1$. This implies that $U_s = U_r$ and angle $\psi = 0^\circ$. Correspondingly, at $k_y = 1$ we obtain that $K = \frac{1 + a}{1 + a^2} = a$. This means that $U_s = aU_r$ and angle $\psi = 120^\circ$.

From the equation of the electromagnetic balance, the complex coefficient of transformation is defined with respect to the load current. Under the aforementioned conditions we obtain: $\frac{I_s - I_r}{k_y} = a^2 I_r - aI_s$, or $I_r = \frac{1 + a\ k_y}{1 + a^2 k_y} I_s$. Thus, the current transformation coefficient corresponds entirely to the voltage transformation coefficient. At the input and output voltage modules being equal, as it occurs at the idle run mode, we can write as follows: $\dot{K} = \frac{1 + a\ k_y}{1 + a^2 k_y} = e^{j\psi} = cos\psi + j\,sin\psi$.

The basic indices to determine the power and cost characteristics of the device are currents and voltages in its elements.

Voltage U_{sr} between the input and output terminals of the device is as follows:

$$U_{sr}=-\frac{3}{2}k_y\frac{k_y-j\frac{2}{\sqrt{3}}(1-\frac{k_y}{2})}{1-k_y+k_y^2}U_s.$$

Varying during regulation of angle ψ voltage of windings W_1, W_2 и W_3:

$$|U_1|=|U_2|=\frac{\frac{k_y}{2}+\sqrt{1-k_y+\frac{k_y^2}{4}}}{\sqrt{1-k_y+k_y^2}}U_s,\ |U_3|=|U_y|=\frac{k_y}{\sqrt{1-k_y+k_y^2}}U_s.$$

The current in the regulation winding is characterized by the following ratio:

$$I_y=\frac{\frac{k_y}{2}+\sqrt{1-k_y+\frac{k_y^2}{4}}}{\sqrt{1-k_y+k_y^2}}I_s.$$

The most important characteristic of the device is its calculation (typical) power, which can be considered as the index that allows the comparison of the design solutions to be performed:

$$S_{PST}=\frac{(\frac{\sqrt{3}}{2}k_y+\sqrt{1-k_y+k_y^2})(\frac{k_y}{2}+\sqrt{1-k_y+\frac{k_y^2}{4}})}{1-k_y+k_y^2}U_sI_s=(1+sin\frac{\psi}{2})(cos\frac{\psi}{2}+\frac{1}{\sqrt{3}}sin\frac{\psi}{2})U_sI_s.$$

Figure 3 shows the graphs of variations in the power of the known classic two-transformer device S_N and the PST S_{PST} being considered, which prove the efficiency of the use of the device in the ranges of regulation more than $\pm 50°$.

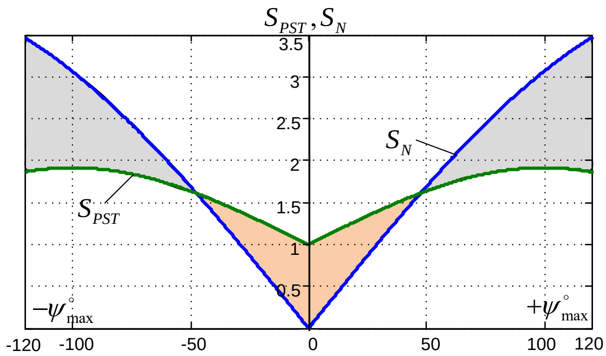

Fig. 3. Graphs of changes in calculation power.

Based on the structural-simulation model in the medium Matlab/Simulink, for the PST (Fig.1), the mode parameters were determined. Figure 4 shows, as an example, the graphs of currents and voltages in the device elements in the mode of a load.

The lines exhibit the characteristics obtained on the basis of the mathematic model and the dots - at the structural-simulation modeling. The data obtained at various kinds of modeling are seen to correspond.

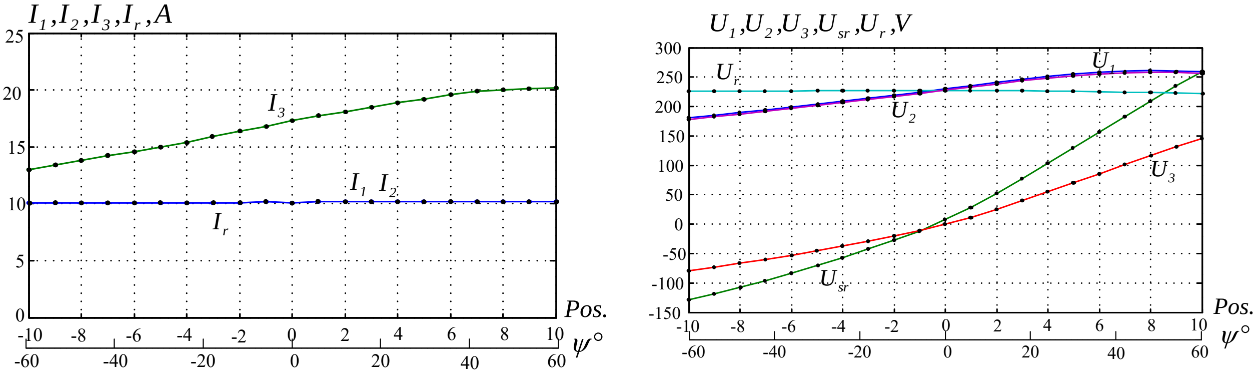

Fig. 4. Graphs of currents and voltages in the elements of device performed in single-transformer with regulation in neutral scheme.

The main elements of the ‘triangle’ scheme device (Figs. 5, 6) are composed of two power transformers, one of which ‘p’ carries out the functions of a parallel (or magnetizing) element, the other ‘q’ performs the functions of a successive (phase-shifting) element.

The winding of the high voltage phase-shifting transformer W_{1q} has a middle point ‘m’, to which high voltage terminals of windings W_{1p} of the magnetizing transformer are switched, are connected as a triangle. This kind of switching makes it possible to reach stability of the output voltage in the process of angle ψ regulation.

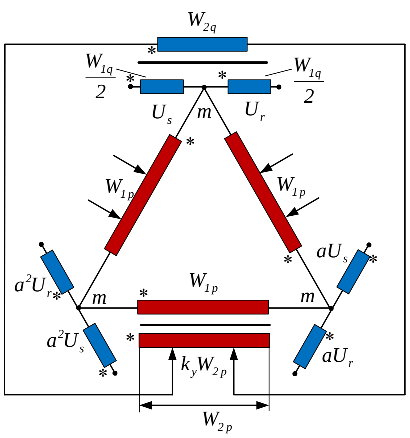

Fig.5. PST ‘triangle’ scheme.

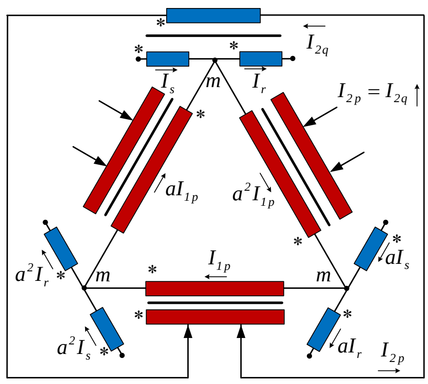

Fig. 6. Current distribution in device windings.

The change in the phase-shift angle between input U_s and output U_r of the device is carried out by means of a mutual displacement of the regulation contacts on the low voltage winding W_{2p}. Based on Figs. 5,6 the equation of the electromagnetic balance of the phase-shifting transformer can be written: $I_s \frac{W_{1q}}{2} + I_r \frac{W_{1q}}{2} = I_{2q} W_{2q}$, as well as the expressions are obtained, which characterize the mode parameters of the device. The expressions for the currents and voltages for the driving and phase-shifting elements are as follows:

$$I_{1p} = \frac{2}{\sqrt{3}} \sin\frac{\psi}{2} I_s, \quad U_{1p} = \sqrt{3}\cos\frac{\psi}{2} U_s, \quad I_{2p} = \frac{\cos\frac{\psi}{2}}{k_q} I_s, \quad U_{2p} = 2k_q \sin\frac{\psi}{2} U_s,$$

$$I_{1q} = I_s, \quad U_{1q} = \frac{U_{2q}}{k_q} = 2\sin\frac{\psi}{2} U_s \quad , I_{2q} = \frac{\cos\frac{\psi}{2}}{k_q} I_s \quad , U_{2q} = U_{2p} = 2k_q \sin\frac{\psi}{2} U_s,$$

where $k_q = \frac{W_{2q}}{W_{1q}}$ is the coefficient of transformation.

The PST research (Fig.5) was performed by analogy with the PST (Fig.1), i.e., with the use of the two kinds of models. Figure 7 shows the graphs of currents and voltages in the device elements under the load. The lines indicate the characteristics obtained based on the mathematic model, and the 'asterisk' symbolizes the use of the structural-simulation modeling.

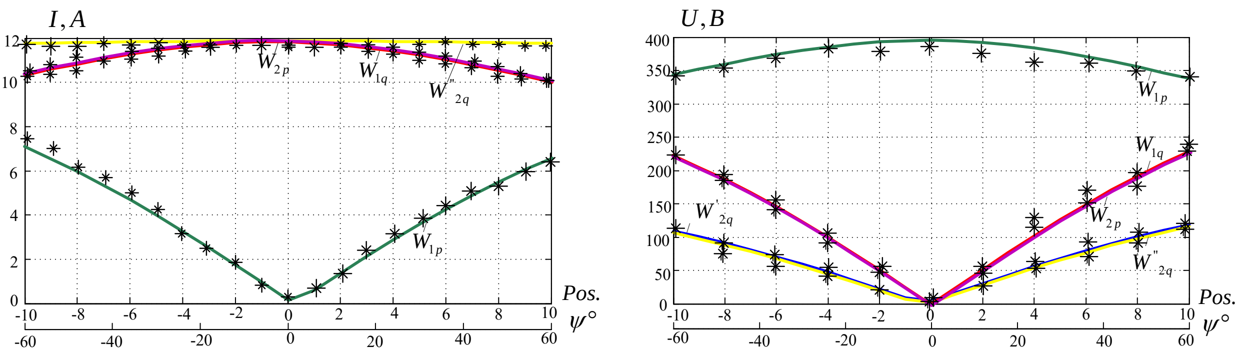

Fig.7. Graphs of currents and voltages in elements of 'triangle' scheme device.

The 'star' PST (Fig. 8) also has a two-transformer configuration.

The scheme of the electric connections of the device on the side of a high voltage is presented in Fig. 8a and the electric connection scheme on the low voltage side is shown in Fig. 8b.

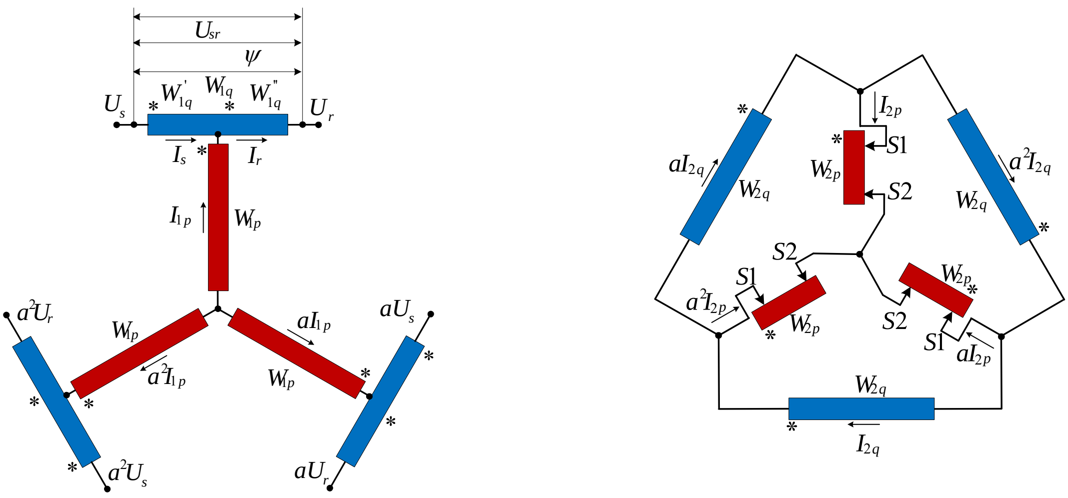

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Fig.8. ‘Star’ PST

The regulation of phase shift ψ of output voltage U_r with respect to input voltage U_s is accomplished using the opposed displacement of contacts $S1, S2$ of the switching mechanism under the load along the taps of low voltage regulatory winding W_{2p} of the magnetizing transformer.

High voltage windings W_{1q} of the phase-shifting transformer have middle points, to which high voltage terminals of winding W_{1p} of the magnetizing transformer are switched, are ‘star’ connected. For the PST (Fig. 8) the following expressions are obtained that characterize currents and voltages for the driving and phase-shifting elements:

$$I_{1p} = 2\sin\frac{\psi}{2} I_s, \quad U_{1p} = \cos\frac{\psi}{2} U_s, \quad I_{2p} = \frac{\sqrt{3}}{k_q}\cos\frac{\psi}{2} I_s, \quad U_{2p} = \frac{2}{\sqrt{3}} k_q \sin\frac{\psi}{2} U_s.$$

$$I_{1q} = I_s, \quad U_{1q} = 2\sin\frac{\psi}{2} U_s, \quad I_{2q} = \frac{\cos\frac{\psi}{2}}{k_q} I_s, \quad U_{2q} = 2k_q \sin\frac{\psi}{2} U_s.$$

The calculation power of the device is: $S_{PST} = S_p + S_q = 4U_s I_s \sin\frac{\psi_{max}}{2}$.

The PST study (Fig. 8) was performed by analogy with the PST (Figs. 1, 5) also based both on mathematic and SPS models. Figures 9, 10 show the curves of changes in the mode parameters of the PST in the process of the phase-shift regulation under the load.

The lines indicate characteristics obtained based on the mathematic model, and the ‘asterisk’ symbolizes the structural-simulation modeling.

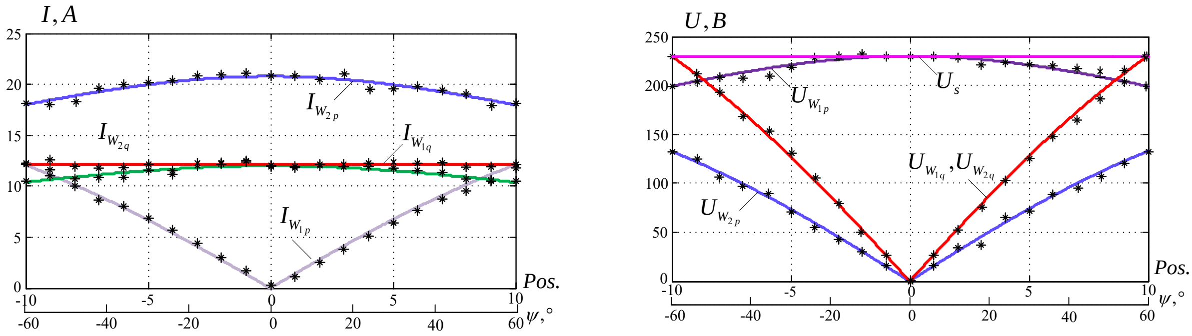


Fig. 9. Graphs of currents and voltages in ‘Star’ device elements.

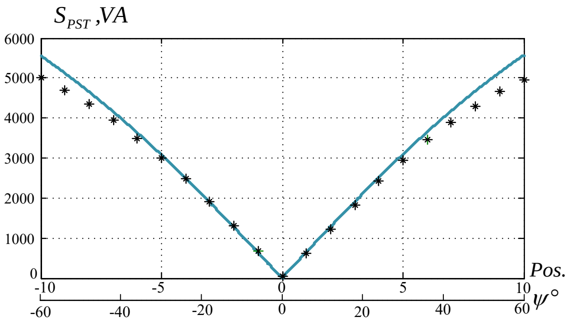
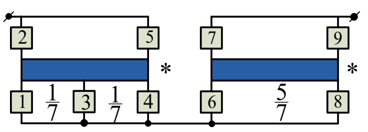


Fig.10. Character of changes in transient power.

The comparative analysis of the mode characteristics of the objectives under study that were obtained using both the mathematic and structural-simulation modeling, indicated agreement between the results obtained. Hence, the decision was taken to use the structural-simulation modeling as the major method for the study of the PST schematic variants being offered further on.

<u>In Chapter 3,</u> ‘COMPARATIVE ANALYSIS OF THE POWER CHARACTERISTICS OF STATIC PHASE SHIFTING DEVICES’, four variants of sectioning the control windings depending on the requirements to the precision of regulation of the output voltage angle, being imposed on the phase-shifting transformer. Each of the regulation variants was offered the laws of switching the power keys, which allowed the necessary range of control to be ensured for the phase-shift angle. The scheme of sectioning the control windings and the laws of switching using the power keys meant for 7, 10, 12, and 15 regulation steps are shown, correspondingly, in Figs. 11—14.



Keys	–7	–6	–5	–4	–3	–2	–1	0	1	2	3	4	5	6	7
1	●					●					●				
2				●	●				●	●				●	●
3		●		●			●		●			●		●	
4			●		●			●		●			●		●
5	●	●	●			●	●	●			●	●	●		
6											●	●	●	●	●
7	●	●	●	●	●										
8	●	●	●	●	●	●	●	●	●	●					
9						●	●	●	●	●	●	●	●	●	●
	Regulation step														

Fig.11. Control winding and switching law for 7 steps of regulation.

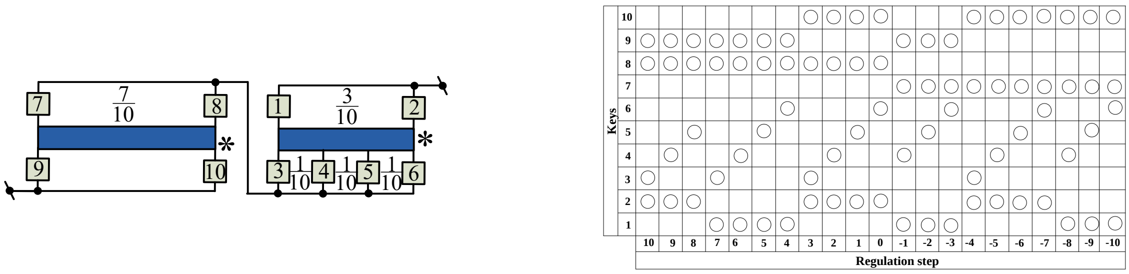


Fig. 12. Control winding and switching law for 10 regulation steps.

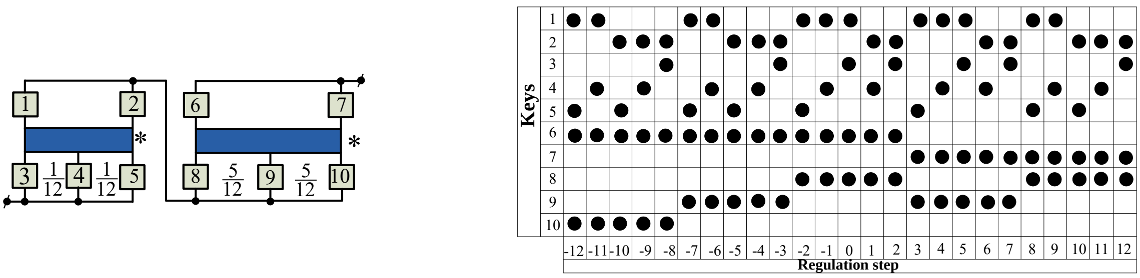


Fig. 13. Control winding and switching law for 12 regulation steps.

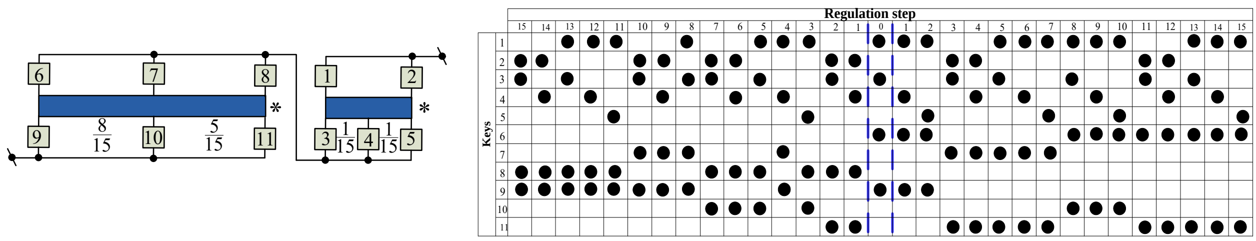


Fig. 14. Control winding and switching law for 15 regulation steps.

Four original PST variants are developed and studied, whose principal schemes are exhibited in Figs. 15—18.

Different strategies and laws of control were used for each variant to ensure the change in the range of the phase shift angle $\psi = 0 \div \pm 60^{\circ}$: a ‘modified triangle’ with a control in accordance with Fig. 13; ‘inverted multangular’ configuration with a control according to Fig. 14; ‘modified multangular’ configuration with a control according to Fig. 12; and “in a hexagonal’ configuration with a control according to Fig. 11.

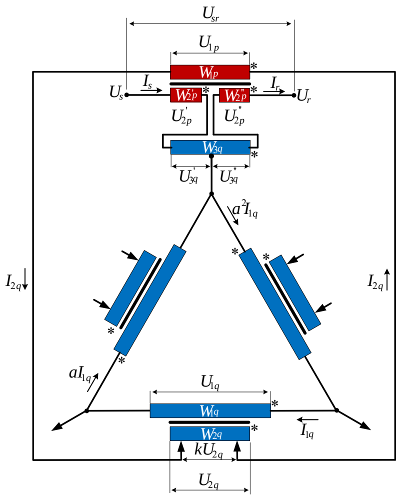


Fig.15. PST scheme, 'modified triangle'

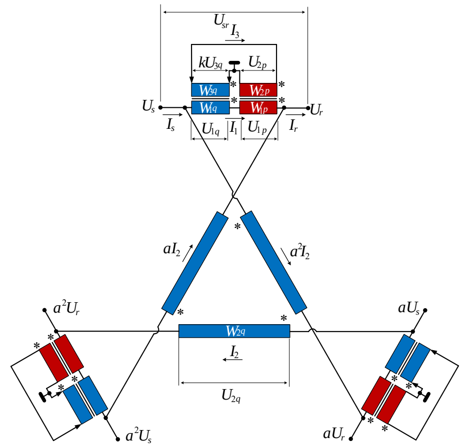
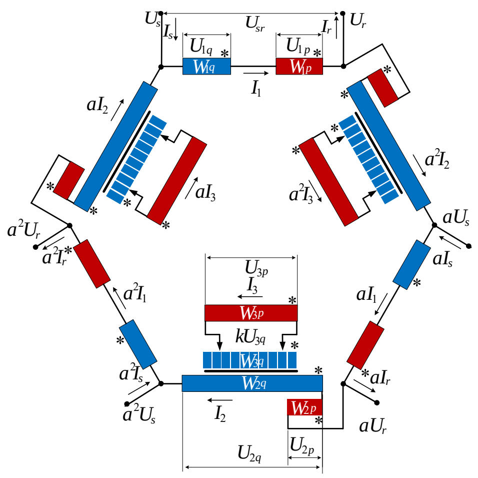


Fig.16. PST scheme, 'inverted triangle'



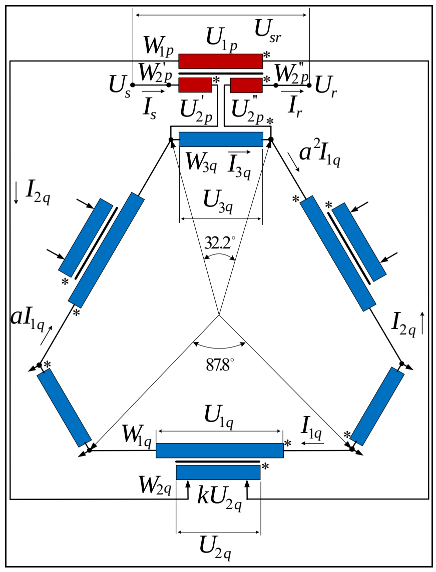


Fig.17. PST scheme 'modified multangular configuration'

Fig.18. PST scheme 'hexagonal configuration'

For each of the schemes under study, the SPS-models were created, based on which, the calculation experiments were performed. The analysis of the obtained results made it possible to determine the PST power characteristics and also to carry out a comparative analysis of the objectives under consideration using the selected criteria:

S_{PST}/S_r - the coefficient that characterizes the device established power;

S_{PE}/S_r - the coefficient that characterizes the power of the control means.

The results of the comparative analysis are presented as the diagram in Fig. 19.

1. ‘star’
2. ‘single-transformer PST with regulation in neutral point’,
3. triangle’
4. ‘modified triangle’,
5. ‘inverted triangle’,
6. ‘modified multangular configuration’,
7. PST in hexagonal configuration.

Fig. 19. Power characteristics of PST schematic variants

As one method for the decrease in the established power of the devices under study, the use of the bank of capacitors was offered that was switched between the PST input and output (technology of the Assisted PST)

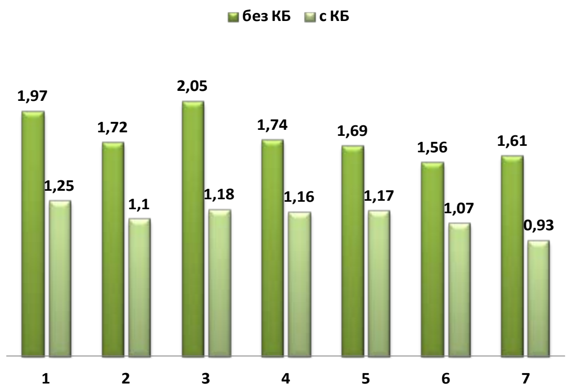


Fig.20. PST established power using bank of capacitors.

The results of the structural-simulation modeling allowed the parameters of the bank of capacitors to be determined and the efficiency of the propose method to be shown (of the capacitive transmission of the part of the power) for the significant decrease in the standard PST power (Fig. 20).

The information presented in Figs. 19, 20, made it possible to infer that the PST (6,7) have the lowest indices with respect to the established power. The results obtained, can be used for the comparative analysis of the schematic PST variants to be developed in future.

Chapter 4, THE PST APPLICATION AS THE ELEMENT OF THE COMBINED FACTS’, describes the mode parameters of the electric connection, which includes the PST frequency converter.

Figure 21 shows a schematic variant of a single-channel PST frequency converter.

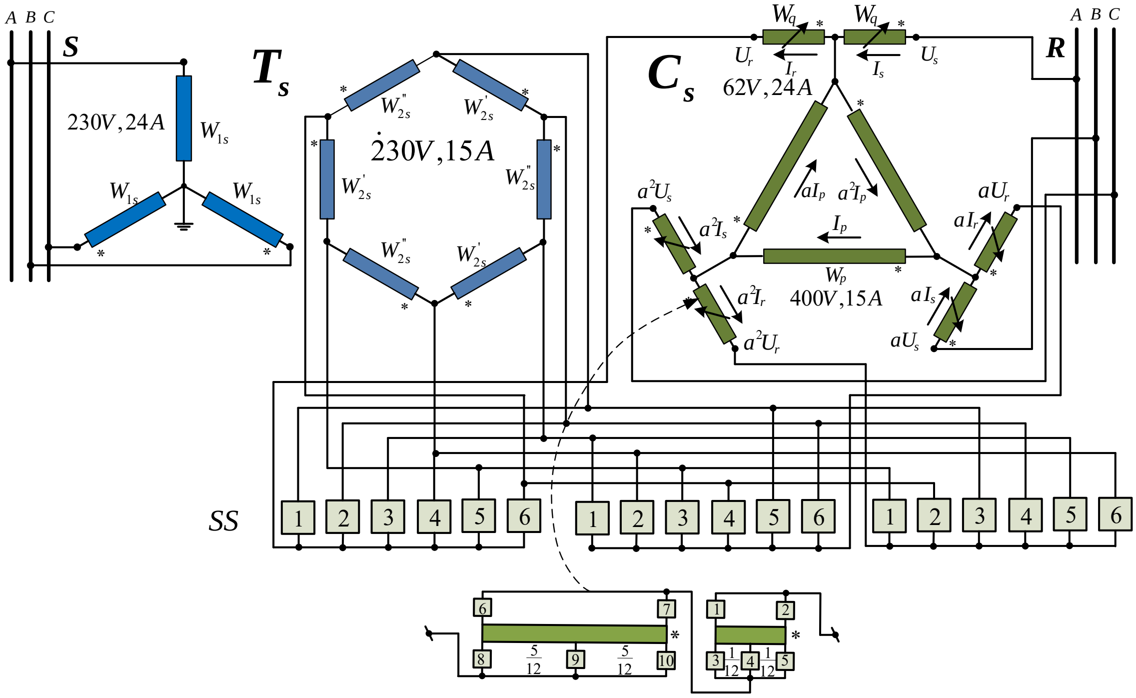


Fig. 21. Scheme of single-channel frequency converter

The converter major element is the phase-shifting transformer C_s, each phase of which includes uncontrollable operating windings and two similar control windings connected in series, forming a triangle, which are switched to the triangle vertices with the middle point of their connection. The control windings are sectioned, and ensure a stepwise regulation of the phase shift at the output of the fine control block. Smoothness of regulation depends on the number of the sections of the operating winding (for the device under consideration it is 12). The strategy of regulation (Fig. 22) is developed to ensure the frequency conversion with discreteness of 2,5° and control winding reverse.

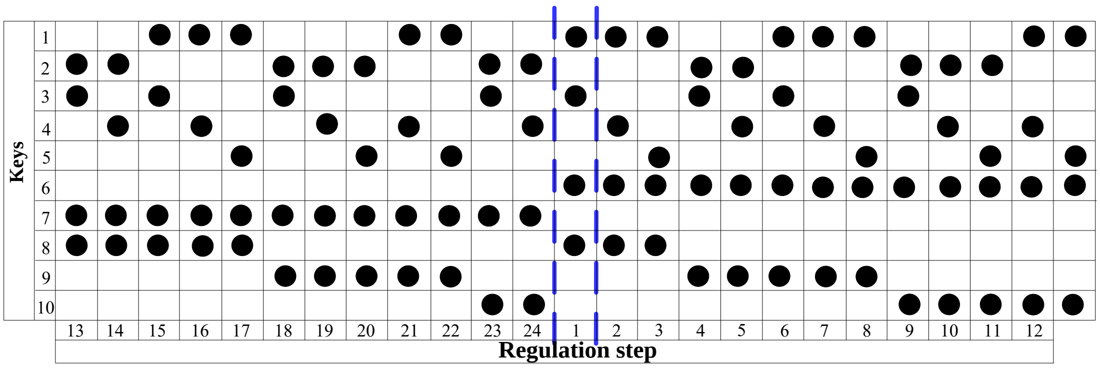


Fig. 22. Strategy of converter control

The primary winding of power transformer T_s is connected to the supply line. The secondary winding of power transformer T_s is performed according to a scheme of a multangular configuration, to the vertices of which a set of simulated power electronic switches *SS* is connected that serve as the block of a converter coarse control. The coarse control block divides the transformation circle into six sectors (each 60°), within the limits of which the fine regulation block operates. Switching of the operating winding sections ensures the stepwise change in the angle of the phase-shift voltage at the output with respect to the voltage supplied in the range of from 0 to 360^0. Based on the structural-simulation model, the calculation experiments were performed using the scheme of Fig. 23.

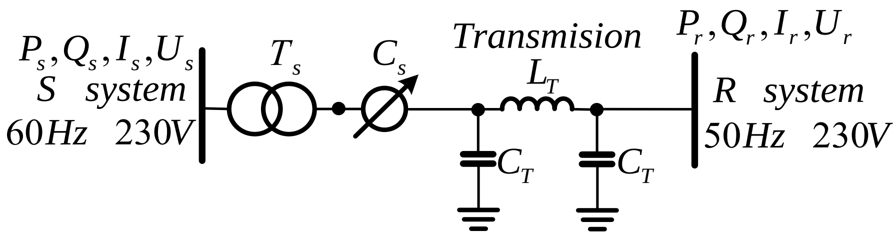


Fig.23. Scheme of experiment at parallel operation of two power systems through frequency converter and power transmission line (PTL)

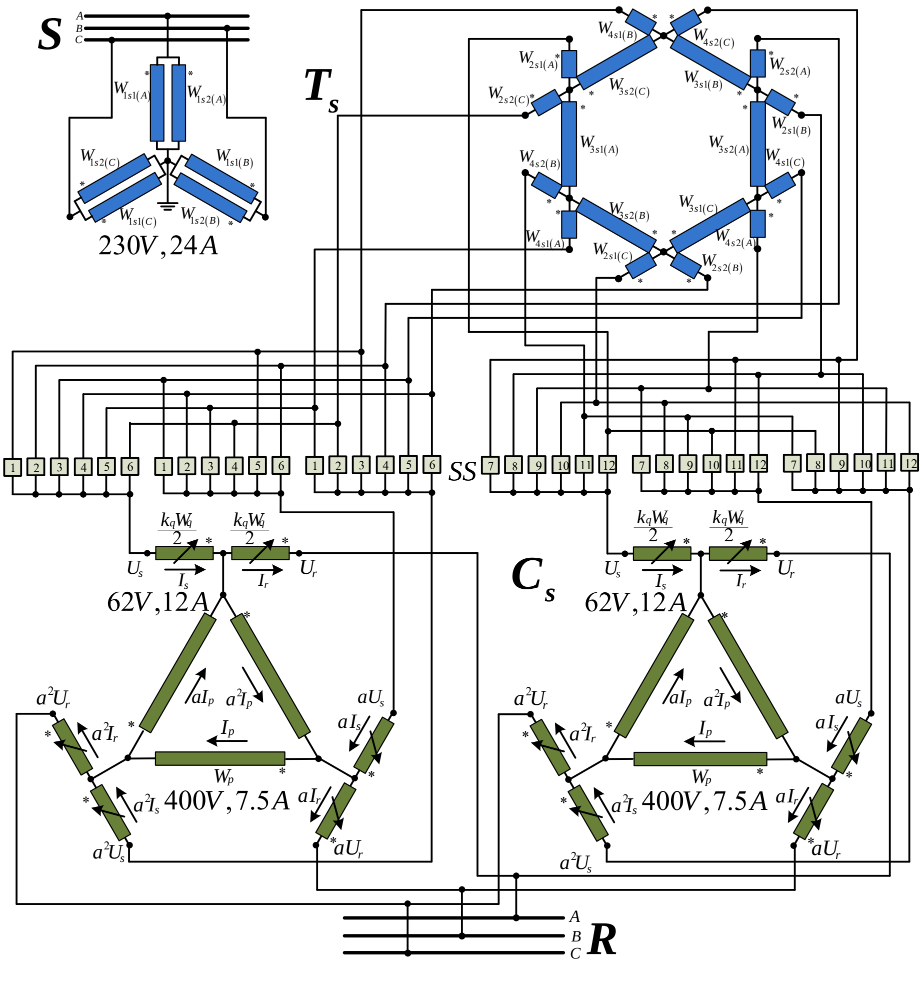


Fig.24. Scheme of two-channel frequency transformation

To improve the frequency transformation quality and enhance stability of the power transferred without the use of any special means, a two-channel converter was offered (Fig.24) with a 30^0 – phase shift between the voltage channels, which reduced substantially the oscillations of the active power in the transmission during the process of the frequency agreement. This allowed the number of the power elements to be significantly reduced, which can improve the operation reliability and make cheaper the device (Fig.26). The converter (Fig.26) comprises by 12 power keys of coarse regulation more and by 24 power keys of fine regulation less compared to the scheme variant (Fig.24). It is noteworthy that for both variants the total power of the coarse regulation keys remains the same.

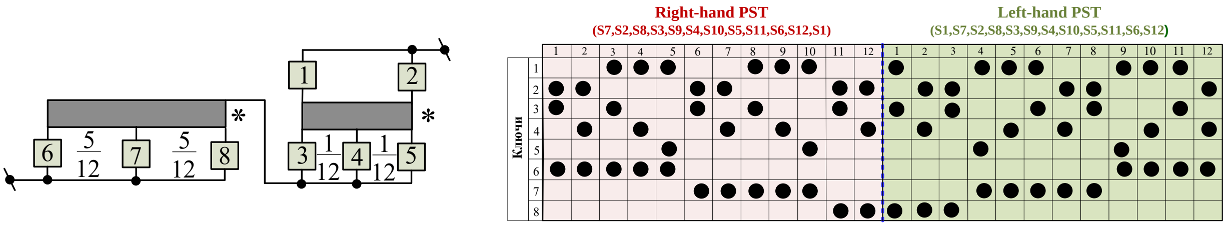


Fig.25. Winding and law of control to ensure 'reserveless' strategy of control

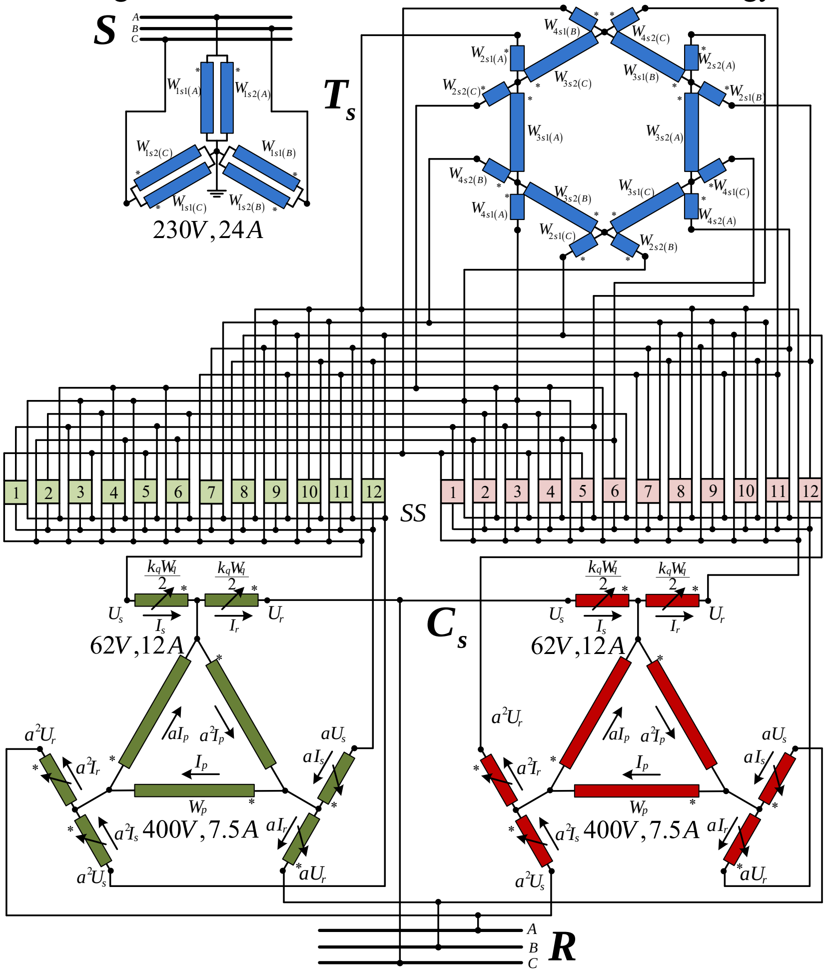


Fig.26. Scheme of two-channel transformer based on 'reverseless' strategy of control

To compare the schematic variants of transformers from the viewpoint of quality of agreement on frequency and power transmission, the following indices are used:

- Deviation of the active power transfer at the transmission $\partial P_s,\%$ and receiving $\partial P_r,\%$ systems from the preset magnitudes;
- Coefficient of the electric current harmonic distortions at the transmission $THD(I_s),\%$ and receiving $THD(I_r),\%$ systems.

The results of the performed calculation experiments exhibited an undeniable advantage of the ’reverseless’ two-channel scheme of the transformer (Figs. 27, 28).

The researches were carried out for the estimation of the effect of the longitudinally switched impedance coils on the quality of transformation. The inductance values were determined of the impedance coils in the range of 0.03—0,035 H that ensure the best characteristics of the transmission. The efficiency of the use of the inductive elements (impedance coils) was proved to improve the qualitative characteristics of transformation with regard to power and frequency (Figs. 29, 30).

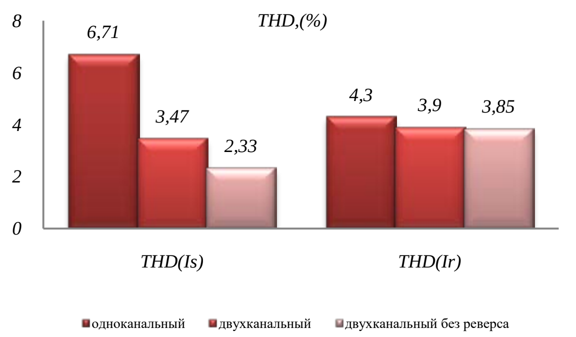


Fig.27. Coefficient of nonlinear distortion of currents both on transmission and receiving systems.

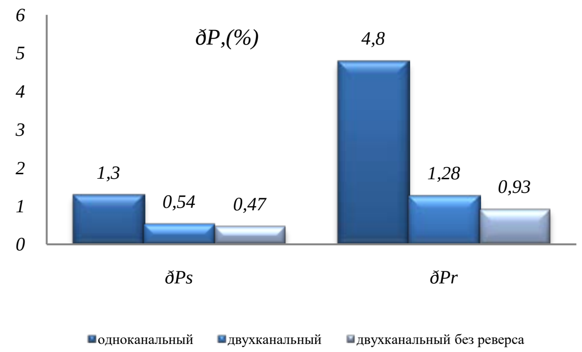


Fig.28. Deviation of transmitted active power on transmission and receiving systems.

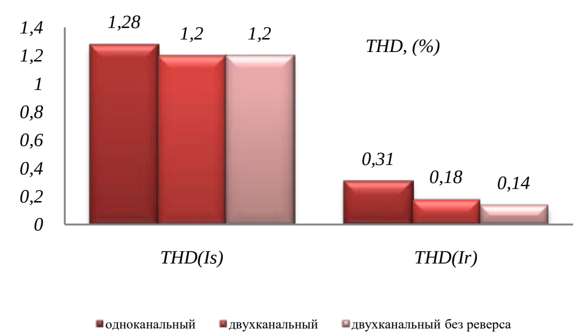


Fig.29. Coefficient of nonlinear distortion of

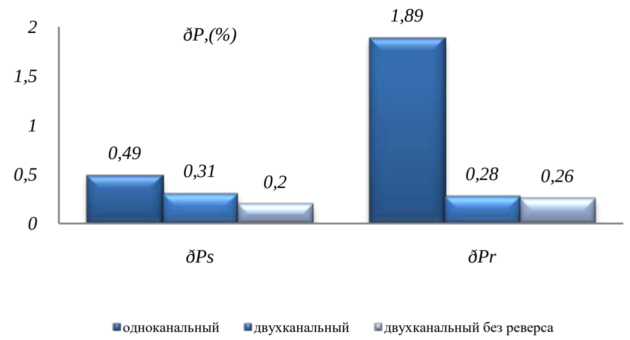


Fig.30. Deviation of transmitted active power on

currents on transmission and receiving systems

transmission and receiving systems

Figure 31 shows a principal scheme of a PST-regulated FACTS-controller that was proposed and studied, which functions as a source of the reactive power.

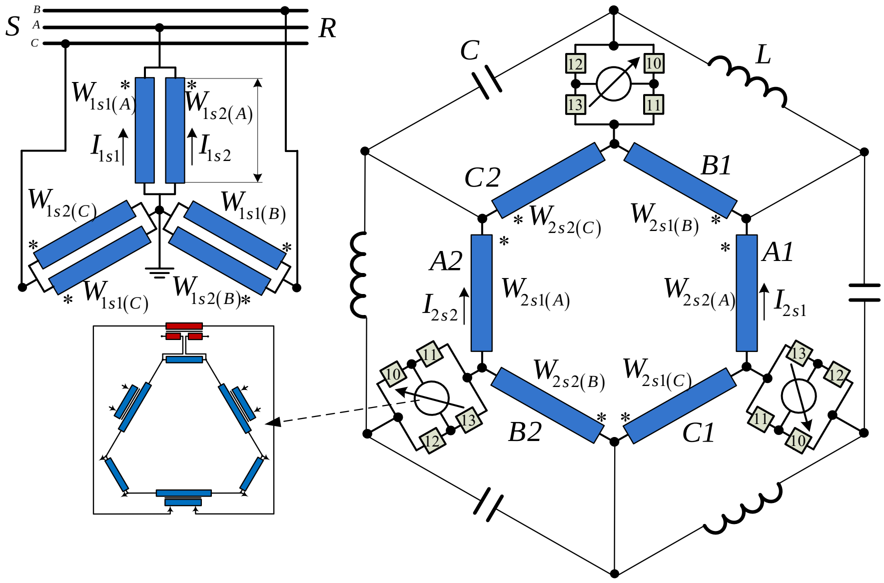


Fig.31. Scheme of regulated source of reactive power

The device offered consists of a transformer, whose primary windings are connected in couples to form a 'star' and are switched into a line break. The secondary windings of it are connected as a hexagon. A phase-shifting transformer is connected by individual phases to the vertices of the hexagon, and there is a possibility of reversing. It also includes conjugated reactive elements *L* and *C* with equal resistances, which are connected to the device through the reversible PST. It is shown that the proposed technical solution ensures a symmetric regulation of the input current of the device and the reactive power both of capacitive and inductive character in a wide range in the point of connection of the device to the network (Figs. 32, 33).

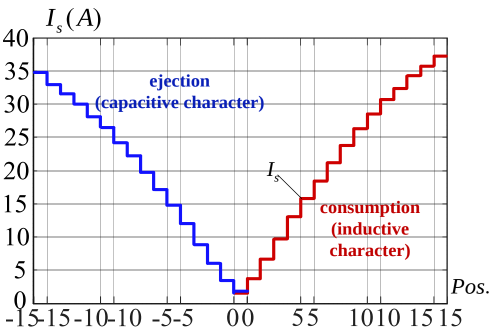


Fig.32. Graph of device output current changing

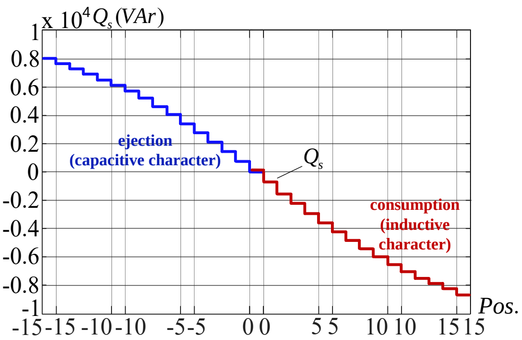


Fig.33. Graph of ejection and consumption of reactive power

The developed PST-based FACTS-controllers can be used as the active elements to regulate the modes of modern Smart Grid power systems.

<u>Chapter 5.</u> 'LABORATORY SAMPLE OF THE PHASE-SHIFTING TRANSFORMER'

To construct the laboratory physical model a schematic PST variant was selected with the lowest index of the established power with the use of the Assisted PST technology. The structural-simulation model of the device, based on which the calculation experiments were performed that allowed the characteristics of the laboratory sample to be verified (Table 1).

Table 1. Laboratory sample characteristics.

Transformer	series (q)					parallel (p)		
core cross section *мм*^{2}	67					53		
power, *P*, *W*	1958					1235		
winding	W_{1q}	W''_{2q1}	W''_{2q2}	W'_{2q}	W_{3q}	W_{1p}	W'_{2p}	W''_{2p}
voltage. U,B	332	38	38	189.5	132.8	265.5	66.8	66.8
ток I,A	6	4.5	4.5	4.5	5.7	4.3	10	10
number of coils, items	157	18	18	89	63	156	39	39
wire diam., *mm*	1.7	1.5	1.5	1.5	1.7	1.47	2.2	2.2

Using the database of Table 1, the single-phase modules of the device were manufactured (Figs.34, 35).

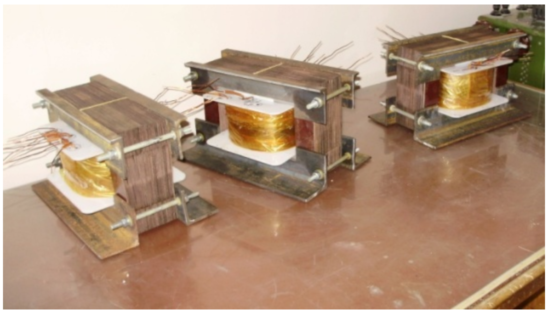


Fig.34. PST driving elements

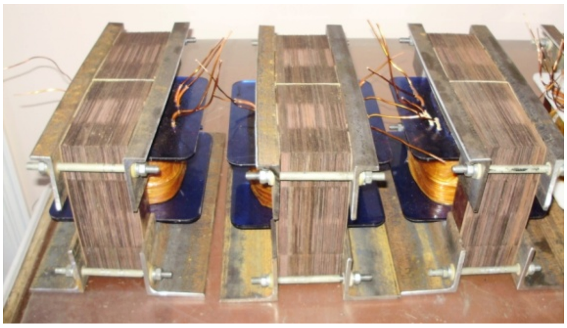


Fig.35. PST series elements

Testing the single-phase power modules in different regimes showed the identity of their characteristics (Figs.36,37) and allowed inference on possibility of their application as the component elements for the laboratory sample.

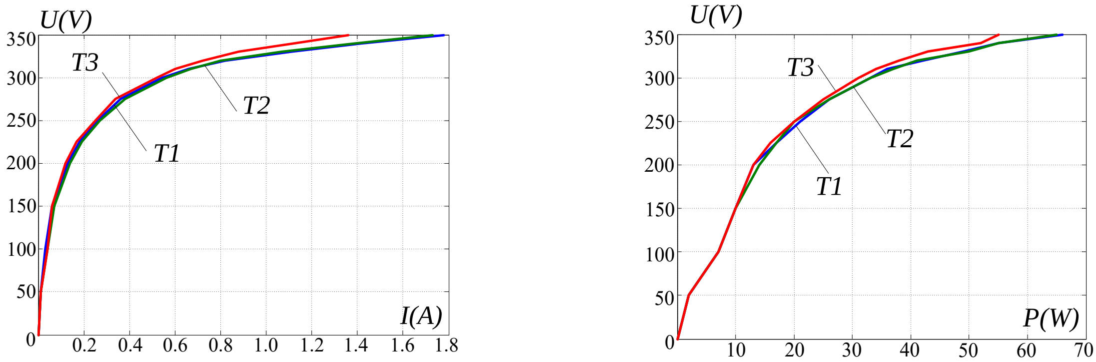


Fig.36. Graphs of current and losses in driving elements in idle run mode

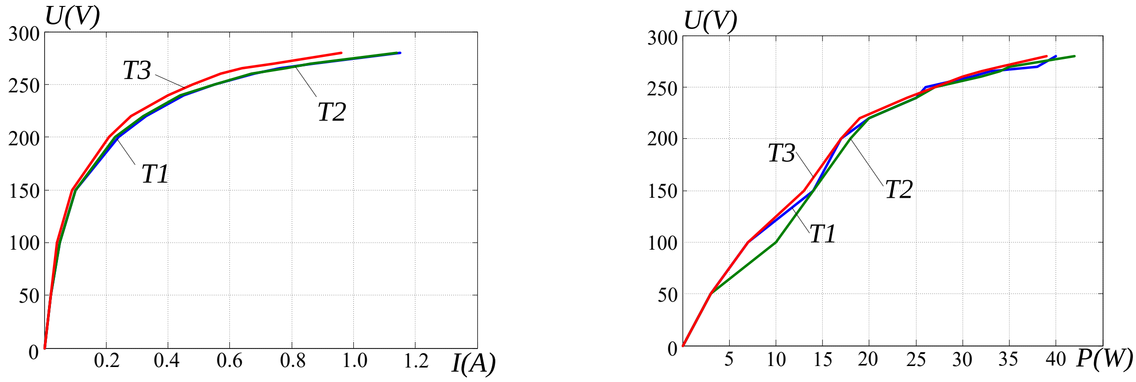


Fig.37. Graphs of current and losses in serial elements in idle run mode

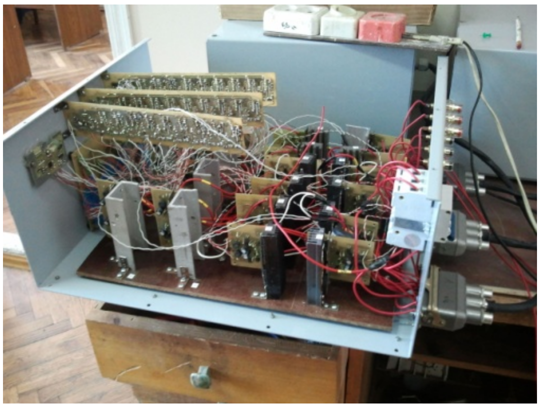


Fig.38. Exterior appearance of electronic module

Fig.39. General view of laboratory sample with nominal power of 10 kW

The connection scheme was developed of the power (Figs. 34, 35) and electronic (Fig.38) modules, which allowed the assembly of the laboratory model as a whole (Fig.39).

The ready for use laboratory device is composed of 3 modules: 3 power single-phase modules (3.3 kW each) and 1 electronic module of control. The laboratory sample was tested in the entire range of control of the phase-shift angle in characteristic modes. The testing results showed a good quality of manufacturing and consistent operation of the regulation windings. Also, the coefficient of efficiency of the manufactured device was determined (94%).

The comparative analysis of the mode parameters showed their good agreement with the characteristics obtained at the structural-simulation modeling.

As an example, Fig.40 shows the dependences of the preset and real phase -shift angles on the regulation step. It can be stated that the difference between the preset and real phase- shift angles is up to 2.97%.

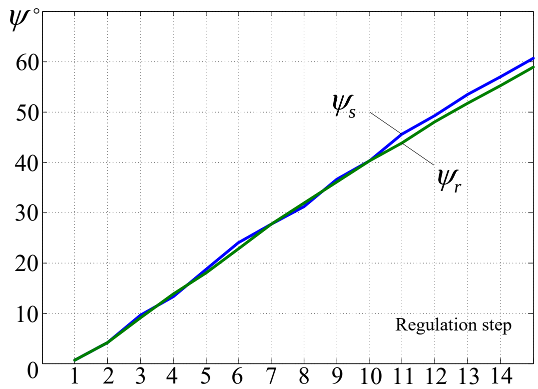


Fig.40. Dependences of calculation and real magnitudes of phase-shift angle

The testing results of the physical model proved the efficiency of the accepted technical solutions (the use of the Assisted PST technique, improvement of the commutation scheme and of the law of control), which reduced substantially the PST mass-dimension indices and optimization of the regulation process.

General conclusions

1. The possibility of the PST application is shown as an element for solving the problems of regulation by the modes of modern actively-adaptive networks.
2. The PST specific character, methods for regulation of the phase-shift angle, typical variants of a schematic performance are studied.
3. The world PST application experience is analyzed and the development of the novel engineering designs in this area is shown to be urgent.
4. The methodological tool for the study of the PST schematic variants is determined and justified.
5. The system of the control windings sectioning is proposed along with the laws of the power keys switching to implement the required strategy of control.
6. The efficiency of the method is shown for the PST established power decrease based on the capacitance transmission of part of the power.

7. The most attractive schematic variants are defined.
8. The functional operating ability of the developed original FACTS-controllers regulated by the PST was confirmed.
9. Based on the PST hexagonal scheme using the module principle, the laboratory sample was manufactured, whose testing exhibited the relevant results that were obtained at various methods of modeling.

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ABSTRACT

The author is Irina Golub. **The title** is '**The Use of the Power Transformers for the Regulation of the Power System Operation**'. Dissertation for awarding the doctor-degree in the region of technical sciences, speciality 221.01. Power systems and technologies. Chisinau, 2020.

Structure of the work: the dissertation includes introduction; five chapters; conclusions; references, which contain 168 sources and 7 appendices; there are 138 pages of the main text; 15 tables and 117 figures; 18 scientific works are published based on the research results.

Keywords: phase-shifting transformer, mathematic modeling, structural-simulation modeling, strategy of control, power characteristics, combined FACTS, laboratory sample

Region of study: technical sciences.

Target of dissertation: The development of FACTS-controllers based on the phase regulation and study of their mode characteristics using means of mathematic and structural-simulation modeling, as well as the approbation of solutions that ensure improvement of the technical characteristics of the objectives under consideration.

Dissertation tasks: Creation of schematic variants of the FACTS-controllers under the phase control based on the power electronics and their study on the basis of mathematic, structural-simulation and physical models for the purpose of approbation of the decisions taken and optimization of the constructive and technical parameters of the devices.

Scientific novelty of the work: consists in the development of the research and optimization of the parameters of the FACTS-controllers schematic variants with a phase regulation.

Scientific problem solved: consists in determination and optimization of constructive and technical characteristics of the FACTS-controllers based on the phase control, which allow the efficiency, flexibility and reliability of the work of the joined power systems to be improved in the context of introduction into the SMART GRID.

Theoretic importance: The results of the work can be a stimulus for the theoretic investigations in the sphere of development, creation and application of the FACTS-controllers regulated by means of the power electronics as a basis for the intellectual actively-adaptive networks.

Application relevance of the work: Materials of the work can serve as a basis for the development and design of the means of control for the modes of intersystem (interstate) connections to solve problems of diversification of the electric energy supplies and liberalization of the energy market in Moldova Republic.

GOLUB IRINA

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221.01 – POWER SYSTEMS AND TECHNOLOGIES

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