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STUDY OF FLEXIBLE INTERCONNECTING MAINS BASED ON TRANSFORMER FREQUENCY CONVERTERS

221.01 – POWER SYSTEMS AND TECHNOLOGIES

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Urgency of the research

The process of integration of the electric power systems and formation of the interstate electric connections (ISEC) and associations (ISEA) is a global tendency as old as almost a hundred years. The perspectives of the ISEC and ISEA development have already been formed long ago, are still being formed at present, and are researched in various areas of the world. Up to date in Europe, the joined ISEA "ENTSO-E" has already been functioning, including more than forty network and system operators from 36 European countries.

Along with the (ISEC) and (ISEA) formation, the magnitude of disturbances increases in the power systems upon the malfunctions caused by load disconnect, transmission lines or energy sources switching off. The transient processes, occurring in the power systems, not always can be efficiently eliminated owing to the insufficient control by the major elements of these power systems either in the automatic or manual modes.

At present, the problem is urgent of enhancing the controllability of the electric networks using special technical means. One direction of the complex solution of the aforementioned issues is a creation and implementation of the controlled interconnecting mains (CICM) in the power systems.

Thus, the elaboration of the proposed advantageous static transformer frequency converters seems promising for the engineering of the alternating current controlled interconnecting mains (AC CICM).

Aims and tasks of the research:

The aim of this work is to perform theoretic and calculation-experimental studies of the AC CICM based on the static transformer frequency converters.

To reach the preset aims the following problems are to be solved:

1. the mathematical models' development of the devices based on the constant current sources and static converters with a circular transformation of the output voltage phase;
2. the elaboration of new schematic variants of the devices based on the constant current sources and static converters with a circular transformation of the output voltage phase;
3. the development of structural-simulation models and laws of control by the modes of operation of the devices based on the constant current sources and static converters with a circular transformation of the output voltage phase;
4. the study of the devices in static and dynamic states;

5. the study of the inherent modes of operation of the converters during the AC CICM engineering;
6. justification of the expediency of a future research in the field of the AC CICM engineering based on the static transformer frequency converters.

Scientific novelty of the results obtained is as follows:

1. the mathematic model of the static frequency converter is developed based on the constant current sources, which allows determining the region of existence of the power transfer modes, as well as the static characteristics of individual elements;
2. the mathematic model of the static transformer frequency converter was developed, which confirms the capability of such a device to be used as a frequency converter;
3. the electric schemes (such as 'zigzag' and 'hexagon') of the static converter were developed based on the constant current sources and static transformer frequency converters;
4. the laws of control by the device operation modes were elaborated based on the constant current sources and static converters with a circular transformation of the output voltage phase for the AC CICM engineering.

Theoretical and practical assets of the work results are the following:

1. The developed mathematical model of a static frequency model, which makes it possible to exhibit the broad picture of the operating modes, as well as the characteristics of separate elements of the converter, can be applied for performing theoretical and experimental studies of the devices of such a kind in the static operating modes;
2. The results obtained during the research of the static transformer frequency converters can serve as the basis for a deeper and more detailed study of the AC CICM in terms of optimization of schematic solutions and laws of control by the devices of the kind.

Techniques and methods for the research:

In the process of the research, to solve the preset problems general scientific methods were used that comprised certain general-logic approaches, methods for systematization of scientific knowledges, and methods for the mathematical and simulation modeling.

As the fundamental research methods, the mathematical and simulation modeling of the research objectives were used. At the simulation modeling, the system under study is replaced with a model that fairly precisely describes the real system, which is used to carry out the calculation experiments in order to obtain information on this system. As the tool for the simulation modeling of the objectives, the medium of the dynamic interdisciplinary modeling of complex technical systems appears to be. It realizes a two-stage approach for the solution of the electric power problems, along with the algorithms of integration with a variable step, which allow fulfillment of highly precise modeling of real elements in the electric power systems.

The dissertation major concepts to be defenced:

1. Mathematic models of the converters based on the sources of the constant current and static transformers with a circular transformation of the output voltage phase;
2. The laws of control by the static frequency converters based on the sources of the constant current;
3. Strategy of control by the static frequency converters based on the static transformers with a circular transformation of the output voltage phase to ensure the process of matching with regard to frequency of the power systems operating in parallel with different frequency standards;
4. Schematic variants of the frequency converters under study for the AC CICM engineering;
5. Methods for improvement of the transformation quality during the AC CICM engineering;
6. Justification of the application expedience of the static frequency converters as the device for the AC CICM.

The degree of authenticity and approbation of the results

The authenticity of the results obtained is confirmed by the consistency of the performed calculations, using the mathematic description and structural-simulation modeling in the medium of the dynamic interdisciplinary modeling of the complex technical systems.

The major positions and results of the dissertation paper were reported and discussed at the:

1. meetings and scientific-technical seminars of the Institute of Power Engineering of Moldova;
2. 7th International Conference of Modern Power Systems, MPS 2017, Cluj-Napoca, June 06-09, 2017;
3. 10th International Conference "Mathematic Modeling in Education, Science and Industry". Tiraspol, September 28-30, 2017;
4. 8th International Conference on Energetics and Ecological Environment, CIEM 2017, Bucharest, October 19-20, 2017;
5. WEC CENTRAL & EASTERN EUROPE ENERGY FORUM – FOREN 2020, Energy Transition in South East Europe: Opportunities, Challenges, Perspectives Costineşti, Romania, 7-10 September 2020.

The dissertation topic was used in 5 articles, and 3 reports were made at 3 International Conferences.

The dissertation structure and volume The dissertation is a 169-pages type-script text. It consists of 5 chapters, general inferences and a conclusion, 8 appendices. The references include 137 source, 107 foreign among them. The work contains 6 tables and 108 figures.

Keywords: rotary frequency changer, asynchronous controlled interconnecting main, Interphase Power Controller (IPC), multimodule frequency converter, static transformer frequency converter.

MAJOR CONTENT OF THE WORK

Introduction обоснована актуальность исследования, сформулированы цели и задачи исследования, раскрыта научная новизна, теоретическая и практическая значимость исследования, определены методы исследования, сформулированы основные положения, выносимые на защиту, приведены сведения о степени достоверности и апробации результатов.

Chapter 1 presents the review of the existing means for joining the power systems.

At present, the DCL and CCT, as the most studied and extensively used in the power systems of various countries of the world, are used to solve the problem of the CICM engineering. Over the past 60 years in the world, more than 200 projects devoted to the CICM engineering based on the constant current were performed. Key problems of the constant current transmission were studied thoroughly in practice and successfully handled, however, many construction solutions remain as yet to be fairly costly.

The alternative for the constant current transmissions are rotary transformers. In the world there is an AS EMFT (Russia) experimental-production sample and a transformer with a variable frequency of rotation "Variable Frequency Transformer" (VFT) (firm "General Electric").

At present, three VFT projects are implemented. The two first projects were single-channel with a power of 100 MW at the electric power substations of Langlois Hydro-Quebec (Canada, 2004) and Laredo (USA, state Texas, 2007). Both these projects are aimed at joining the asynchronously operating power systems of Mexico and Canada with a USA power system. The third project Linden is the first multi-channel VFT with an overall power of 300 MW aimed at joining the power systems of states of New Jersey and New-York (USA, 2009).

The possibility was also studied of the VFT application for the power systems connection, whose slip frequency was over $\pm 3\,Hz$. The results of the researches showed a principal possibility of construction of the alternating current CICM at a wider range of the slip frequency change. However, in this situation, the facilities of this kind will have an extremely complicated system of control, and will require the use of the compensation devices to maintain the necessary level of voltage on the bus lines, whose power will exceed the established power of the rotary transformer by two times.

Chapter 2 contains the methodological apparatus of the research and mathematical models of the proposed facilities based on the constant current source and the static transformer.

The major general scientific and general-logic methods being applied in the work are presented, which make it possible to handle the problems that are set forth and reach the aims of the research. The methods for mathematic and simulation modeling are fundamental in order to carry out the present investigation. As a tool for the simulation modeling in this work, the medium of the interdisciplinary modeling of complicated technical systems MatLAB – Simulink – SimPowerSystems is considered to be.

The scheme of a static converter was developed with six pairs of the three-phase modules, which consist of two constant current sources equipped with four power keys (Fig. 1), and the mathematic model of the facility is created.

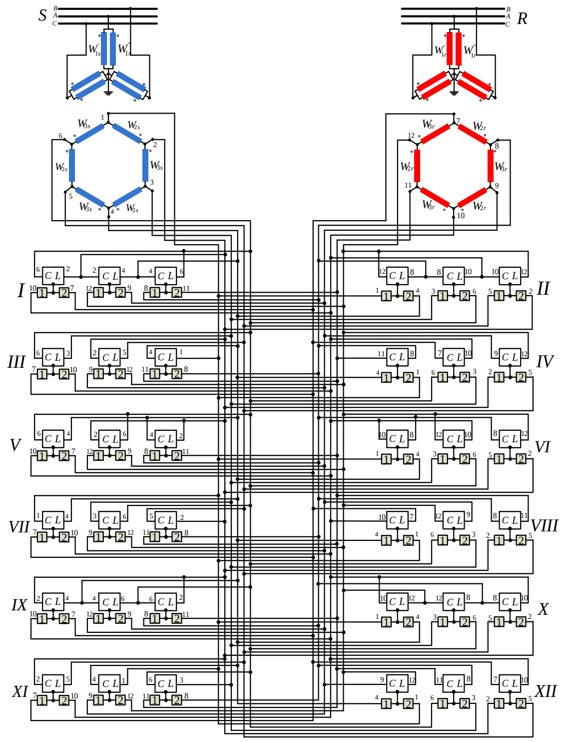


Fig. 1. Electrical scheme of static frequency transformer based on constant current sources.

Based on the combinatorics law, 4 096 nonrecurrent combinations of the keys response, which allow obtaining 361 original level of the transferred power, are shown in Fig. 2, where the direction of transmission of the power transmitting system (S) to the receiving power system (R) is accepted to be positive.

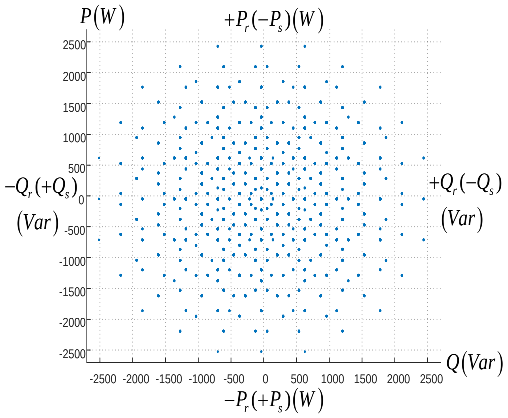


Fig. 2. Complex plane of values of transferred powers at facility input and output.

The value and direction of transmitting active and reactive powers by the facility, depending on the combination of switching on the keys at the paired modules and angle δ_{sr} between the transmitting (S) and receiving (R) systems, are determined using the following formulas:

$$P_m = P_n^{I,II} + P_n^{III,IV} + P_n^{V,VI} + P_n^{VII,VIII} + P_n^{IX,X} + \\ + P_n^{XI,XII} + P_0$$

$$Q_m = Q_n^{I,II} + Q_n^{III,IV} + Q_n^{V,VI} + Q_n^{VII,VIII} + Q_n^{IX,X} + Q_n^{XI,XII} + Q_0$$

where: m - is the number of combination of switching on the keys at the paired modules of the facility from 1 to 4 096; $P_n^{I,II}, P_n^{III,IV}, P_n^{V,VI}, P_n^{VII,VIII}, P_n^{IX,X}, P_n^{XI,XII}$ - is the instantaneous value of the active power being transmitted by a single pair of modules depending on the combination of keys switched on at the paired module, (Table 1); $Q_n^{I,II}, Q_n^{III,IV}, Q_n^{V,VI}, Q_n^{VII,VIII}, Q_n^{IX,X}, Q_n^{XI,XII}$ - is the instantaneous value of the reactive power being transmitted by a single pair of modules depending on the combination of keys switched on at the paired module, (Table 2); n - is the position of keys at the paired modules (1-1, 2-2, 1-2, 2-1); and P_0, Q_0 - are the losses in active and reactive powers in the facility.

Table 1. Instantaneous value of the active component depending on the position of the keys and angle δ_{sr}.

Pair №	Paired modules	Position of keys on paired modules, n			
		1 – 1	2 – 2	1 – 2	2 – 1
1	I, II	$P \cdot \cos\delta_{sr}$	$-P \cdot \cos\delta_{sr}$	0	0
2	III, IV	$P \cdot (-\frac{\sqrt{3}}{2} \cdot \cos\delta_{sr} + \frac{1}{2} \cdot \sin\delta_{sr})$	$P \cdot (\frac{\sqrt{3}}{2} \cdot \cos\delta_{sr} - \frac{1}{2} \cdot \sin\delta_{sr})$	0	0
3	V, VI	$P \cdot (\frac{1}{2} \cdot \cos\delta_{sr} - \frac{\sqrt{3}}{2} \cdot \sin\delta_{sr})$	$P \cdot (-\frac{1}{2} \cdot \cos\delta_{sr} + \frac{\sqrt{3}}{2} \cdot \sin\delta_{sr})$	0	0
4	$VII, VIII$	$P \cdot \sin\delta_{sr}$	$-P \cdot \sin\delta_{sr}$	0	0
5	IX, X	$P \cdot (-\frac{1}{2} \cdot \cos\delta_{sr} - \frac{\sqrt{3}}{2} \cdot \sin\delta_{sr})$	$P \cdot (\frac{1}{2} \cdot \cos\delta_{sr} + \frac{\sqrt{3}}{2} \cdot \sin\delta_{sr})$	0	0
6	XI, XII	$P \cdot (\frac{\sqrt{3}}{2} \cdot \cos\delta_{sr} + \frac{1}{2} \cdot \sin\delta_{sr})$	$P \cdot (-\frac{\sqrt{3}}{2} \cdot \cos\delta_{sr} - \frac{1}{2} \cdot \sin\delta_{sr})$	0	0

Table 2. Instantaneous value of the reactive component depending on the position of the keys and angle δ_{sr}.

Pair №	Paired modules	Position of keys on paired modules, n			
		1 – 1	2 – 2	1 – 2	2 – 1
1	I, II	$Q \cdot \sin \delta_{sr}$	$-Q \cdot \sin \delta_{sr}$	0	0
2	III, IV	$Q \cdot (-\frac{1}{2} \cdot \cos \delta_{sr} - \frac{\sqrt{3}}{2} \cdot \sin \delta_{sr})$	$Q \cdot (\frac{1}{2} \cdot \cos \delta_{sr} + \frac{\sqrt{3}}{2} \cdot \sin \delta_{sr})$	0	0
3	V, VI	$Q \cdot (\frac{\sqrt{3}}{2} \cdot \cos \delta_{sr} + \frac{1}{2} \cdot \sin \delta_{sr})$	$Q \cdot (-\frac{\sqrt{3}}{2} \cdot \cos \delta_{sr} - \frac{1}{2} \cdot \sin \delta_{sr})$	0	0
4	$VII, VIII$	$-Q \cdot \cos \delta_{sr}$	$Q \cdot \cos \delta_{sr}$	0	0
5	IX, X	$Q \cdot (\frac{\sqrt{3}}{2} \cdot \cos \delta_{sr} - \frac{1}{2} \cdot \sin \delta_{sr})$	$Q \cdot (-\frac{\sqrt{3}}{2} \cdot \cos \delta_{sr} + \frac{1}{2} \cdot \sin \delta_{sr})$	0	0
6	XI, XII	$Q \cdot (-\frac{1}{2} \cdot \cos \delta_{sr} + \frac{\sqrt{3}}{2} \cdot \sin \delta_{sr})$	$Q \cdot (\frac{1}{2} \cdot \cos \delta_{sr} - \frac{\sqrt{3}}{2} \cdot \sin \delta_{sr})$	0	0

The analysis of the data obtained made it possible to reveal a cycle out of 71 unique variant of the values of active and reactive powers being transmitted, according to the proposed control strategy in the process of the frequency matching. Figure 3 shows the mode of the maximum level of transmitting the active power component in the process of the CICM engineering of two synchronously operating power systems with different standards of the frequency maintaining.

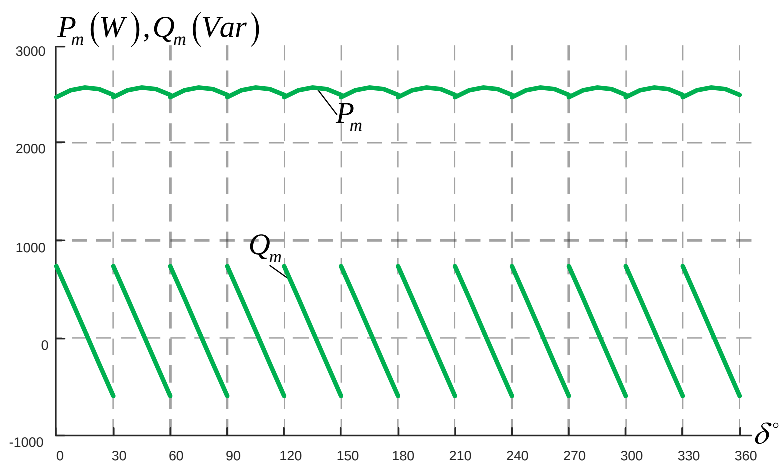
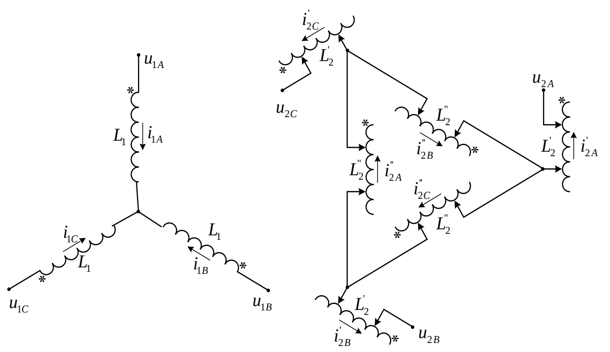


Fig. 3. Sum of calculation values of power modules at static state of facility.

The transformer facility under study has a single three-phase system of the primary windings and two three-phase systems of the secondary windings (Fig. 4). The primary windings form a star. One system of the secondary windings forms a triangle, whose vertices are connected with the relevant phases of the secondary windings of another system. Moreover, each phase of the system of the output voltages is synthesized by way of the geometric summation of the voltages of the corresponding phases of the secondary windings (Fig. 5).



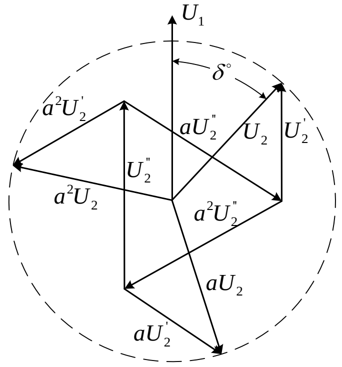


Fig. 4. Scheme of facility variant under study Fig. 5. Vector diagram of powers of facility

For the facility variant under study, the equation systems of the EMF equilibrium for the primary windings was written as follows:

$$u_{1A} - r_1 i_{1A} - p\left(L_1 i_{1A} - M'_{12} i'_{2A} - M''_{12} i''_{2A}\right) = 0$$
$$u_{1B} - r_1 i_{1B} - p\left(L_1 i_{1B} - M'_{12} i'_{2B} - M''_{12} i''_{2B}\right) = 0$$
$$u_{1C} - r_1 i_{1C} - p\left(L_1 i_{1C} - M'_{12} i'_{2C} - M''_{12} i''_{2C}\right) = 0$$

After the transformation of the above equation system with the account of a number of admissions, the expressions were derived, which characterize the instantaneous values of the output voltages of the phases u_{2A}, u_{2B}, u_{2C}:

$$u_{2A} = \frac{1}{k}\sqrt{\frac{L_2}{L_1}} U_1 \sin \omega_2 t - \frac{1-k^2}{k}\omega_1 \sqrt{L_1 L_2} \cdot I_1 \cos\left(\omega_2 t - \varphi\right)$$
$$u_{2B} = \frac{1}{k}\sqrt{\frac{L_2}{L_1}} U_1 \sin\left(\omega_2 t - \frac{2\pi}{3}\right) - \frac{1-k^2}{k}\omega_1 \cdot \sqrt{L_1 L_2} I_1 \cos\left(\omega_2 t - \varphi - \frac{2\pi}{3}\right)$$
$$u_{2C} = \frac{1}{k}\sqrt{\frac{L_2}{L_1}} U_1 \sin\left(\omega_2 t + \frac{2\pi}{3}\right) - \frac{1-k^2}{k}\omega_1 \cdot \sqrt{L_1 L_2} I_1 \cos\left(\omega_2 t - \varphi + \frac{2\pi}{3}\right)$$

where: k - is the coefficient of the inductive coupling of the windings; ω_1, ω_2 - is the cyclic frequency of the transmitting and receiving systems; L_1, L_2 - are the self inductances of the primary and secondary windings.

The expressions obtained contain frequency characteristics of the transmitting and receiving systems, which prove the possibility of realization of the principle of the phase circular rotation of the phase of the output versus the input voltage based on the static transformer facility.

Chapter 3 describes the study of the frequency static transformer based on the constant current sources.

In the process of the research it was confirmed that the structural-simulation and mathematical models illustrate equally the mode characteristics of the facility and of its elements (Fig. 6) by the example of the maximum mode.

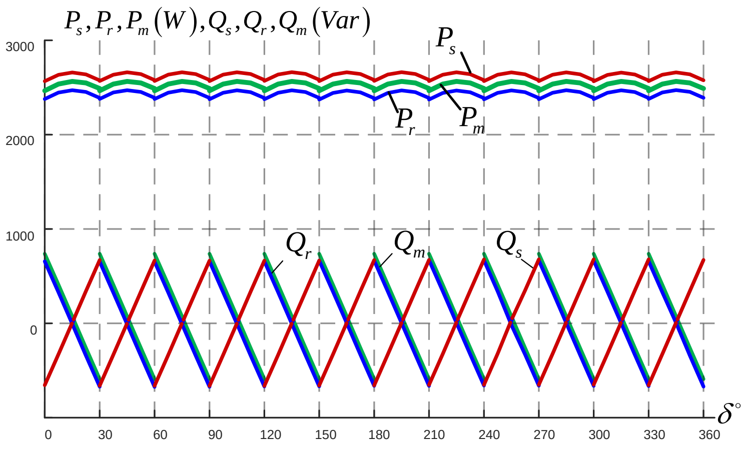


Fig. 6. Values of active and reactive powers at facility input and output under conditions of static state of facility.

The analysis of the graph (Fig. 6) showed that at the moment of the power keys functioning, in the mode of the frequency matching, the commutation of a significant component of the reactive power is found to occur, which affects negatively the quality of transformation. To improve the quality of the transformation process the facility modernization was performed by the addition of the secondary windings to the transformer scheme on the side of the receiving system. This made it possible to realize the phase shift at the angle of at the terminals of each of the pair of windings, which extend from the hexagon vertices (Fig. 7). As to the law of the facility control, the decision was taken to use the asymmetrical control, which consisted in operation of the modules in succession.

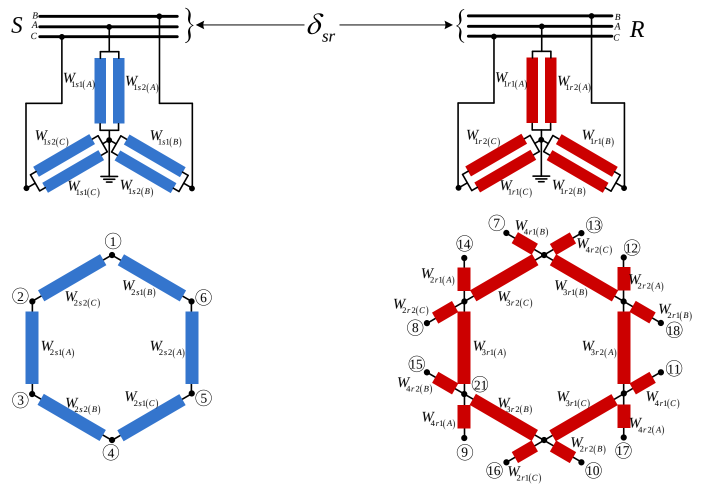


Fig. 7. Electrical scheme of transformer part of converter with mounted additional windings

The proposed technical solution allowed the accompanying reactive power to be reduced by two times in the converter operation process (Fig. 8). The asymmetrical control made it possible to increase the number of the operating modes for the facility power transmission by 6.5 times, from 361 to 2 403 (Fig. 9). Upon the organization of the CICM according to the scheme of (Fig. 7), the value of the coefficient of the current harmonic distortions was no less than 16%, which is undesirable.

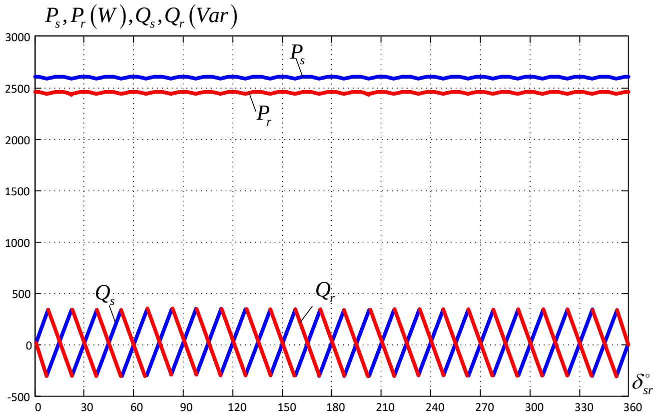


Fig. 8. Static characteristics of power transformer

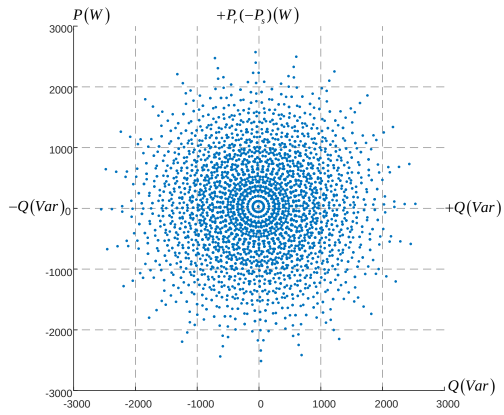


Fig. 9. Region of possible values of transmitted powers

The results of the calculation experiments showed that at the commutation moments, significant current surges are found to occur upon the change in the character of the reactive power from a capacitive component onto inductive and back. To limit the current surges the facility scheme was added another key K3 (Figs. 10, 11). The K3 key, in addition to protection from the current resonance, improves the transformation quality by effectively damping the subsynchronous oscillations (offset) (Fig. 12). This facility modernization expanded the region of modes from 2 403 to 341 097 original levels of the power being transmitted (Fig. 13). Besides, the modernization allowed the coefficient of current harmonic distortions to be reduced owing to determining the optimal time of the K3 key response (8° or $\tau = 0{,}111111$ sec), from 19.6% to 7.02% on transmitting system, and from 16.07% to 8.31% on receiving system (Fig. 14), which fits the requirements of the IEEE-519 standard.

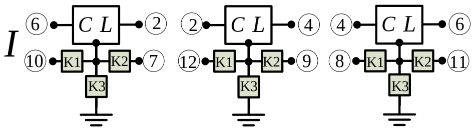


Fig. 10. Principal scheme of elementary module I with key K3.

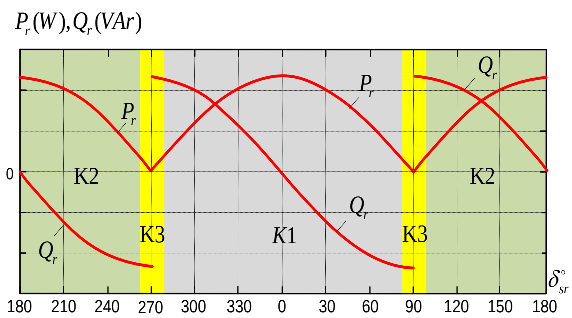


Fig. 11. Change in active and reactive power of a single module

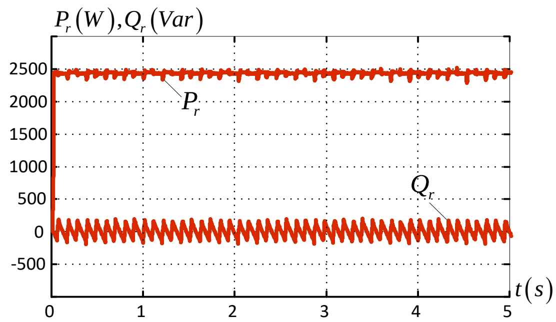
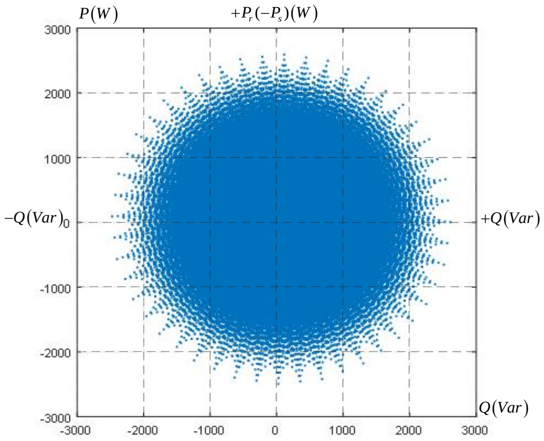


Fig. 12. Operation of transformer with key K3



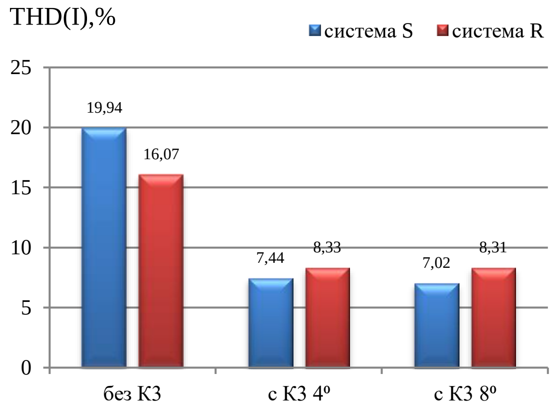


Fig. 13. Region of possible values of transmitted powers at K3 key responce

Fig. 14. Hystogram of coefficients of current harmonic distortion at different K3 key time of responce

The results of modeling confirm that the CICM engineering based on the technical solution accepted makes it possible to: ensure a stable transmission of the active power, reduce substantially the surges of the reactive power, improve the indices of the current harmonic distortions, and decrease the amplitude of the subsynchronous oscillations (Figs. 12, 14).

For a further improvement of the CICM parameters, the harmonic filters and dampers were used, which allowed reducing the current harmonic distortions from 7.02% to 4% at the transmitting system and from 8.31% to 5.07% at the receiving system.

The study results proved that the mathematical model of the facility can be used for determination and analysis of characteristics of the devices of this type. Static transformer based on the constant current sources ensures the control by the mode parameters in a wide range. The developed laws of control by the elementary modules allow the AC CICM systems with different frequency standards to be ensured.

Chapter 4 developed and analyzed the CICM on the basis of the ‘zigzag’ scheme transformer (Fig. 15). The proposed variant of the transformer ensures the circular rotation of the vector of the output voltage versus the input voltage.

Each of the channels of the proposed variant of the scheme of the static frequency transformer consists of the multi-winding single-phase transformer groups SN and SM on the transmitting side and RN and RM on the receiving side, whose primary windings are connected according to the ‘zigzag’ scheme for the purpose of damping the 3 current harmonic. Unregulated secondary windings of the transformers are connected in ‘hexagon’ scheme, whose vertices are connected with corresponding windings of control, which present a block of ‘thin’ control in the range of 60°. Keys 1—6 present the

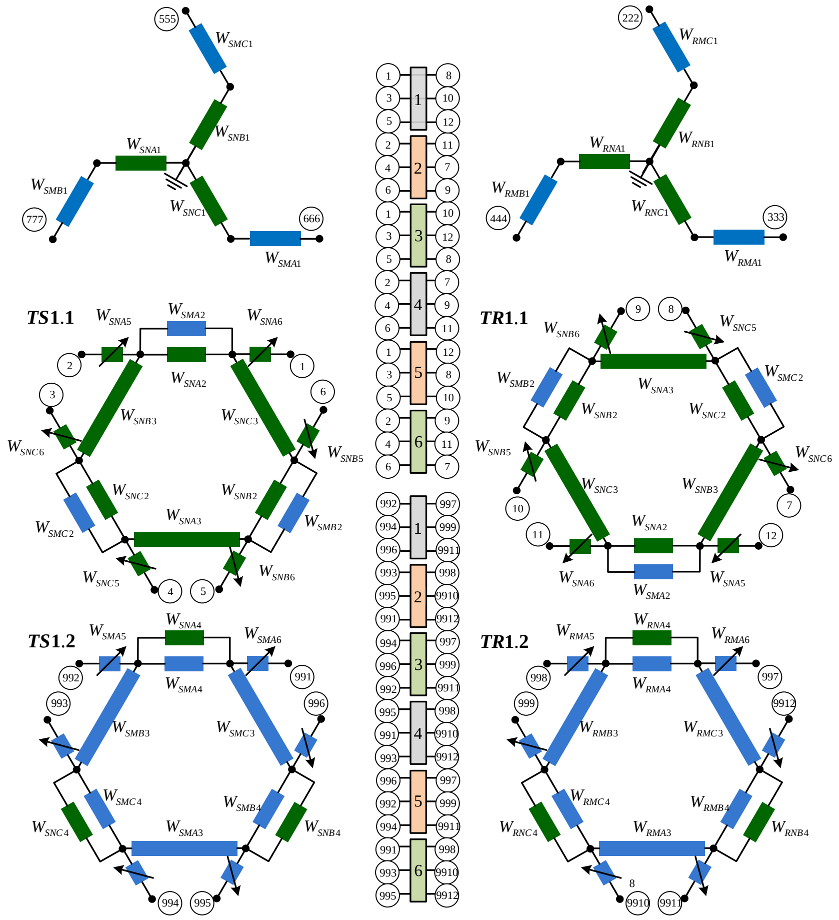


Fig. 15. Scheme ‘zig-zag’ of two-channel static frequency transformer

block of ‘rough’ control with switching over in 120°. The vector diagram of the ‘rough’ control is shown in Fig. 16.

The proposed variant of the transformer ensures the circular rotation of the vector of the output voltage with respect to the input voltage.

To study the op-

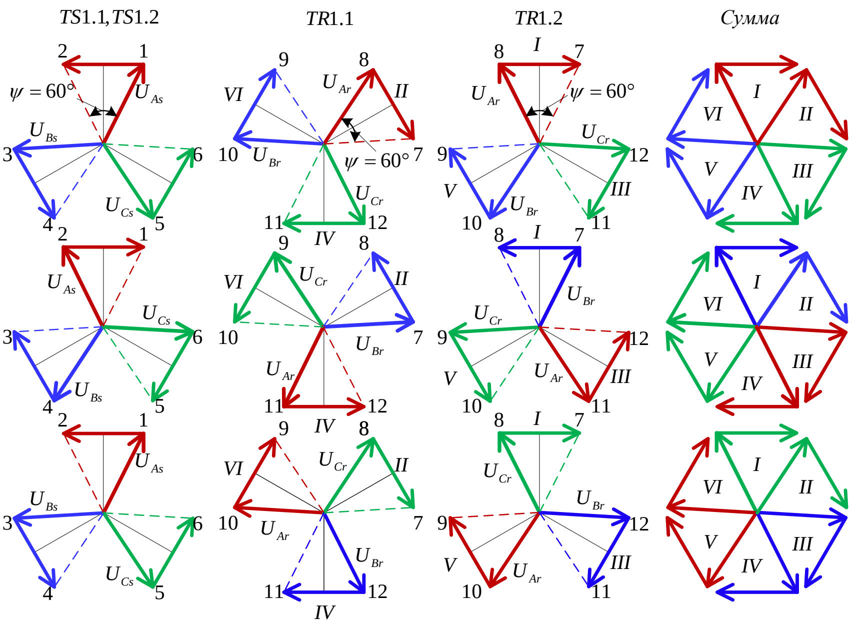


Fig. 16. Vector diagram explaining realization of ‘rough’ control law.

erating modes of the frequency transformer two variants are developed of sectioning the windings of ‘thin’ control and the laws of switching using the power keys for 24 and 48 control steps (Figs. 17—20).

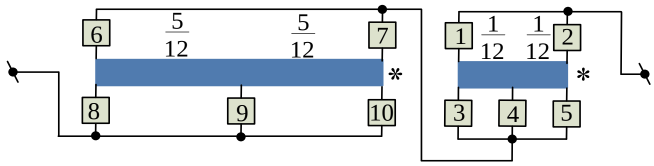


Fig. 17. Scheme of winding sectioning of ‘thin’ control for 24 positions of switching over with 5° step of discreteness

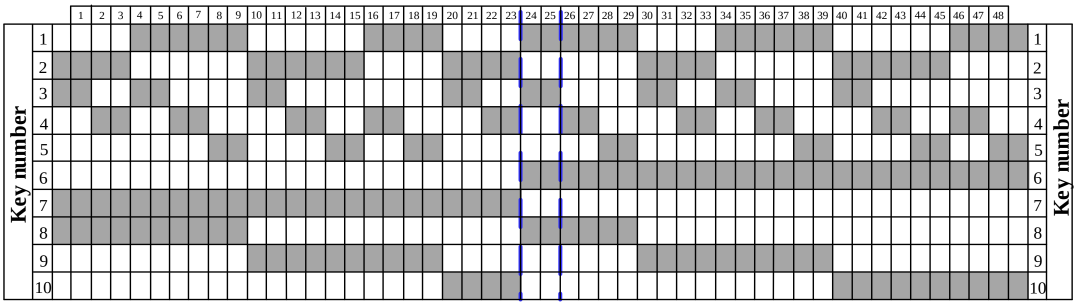


Fig. 18. Law of control using ‘thin’ regulation block with 5° step

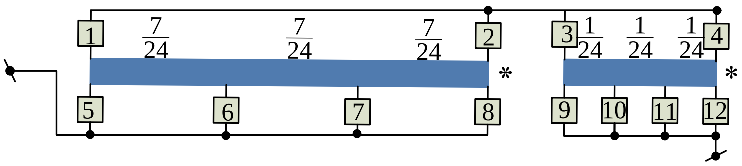


Fig. 19. Scheme of sectioning winding of ‘thin’ regulation for 48 positions of switching over with 2.5° step of discreteness

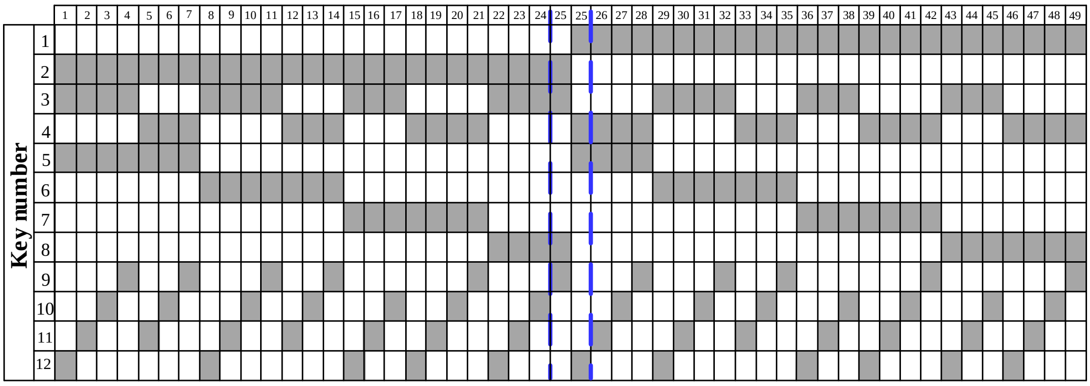


Fig. 20. Law of control by ‘thin’ regulation block with discreteness of 2.5° step

In the Matlab/Simulink medium, the structural-simulation models were created, based on which the calculation experiments were performed upon the facility operation for a load and receiving system through the line (Figs. 21, 22). There were two variants of sectioning the winding of the ‘thin’ control and different ratios of frequencies (Figs. 23, 24) and powers of the transmitting and receiving systems (Figs. 25, 26).

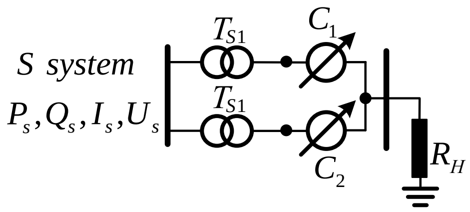


Fig. 21. Scheme of transformer operation for active load

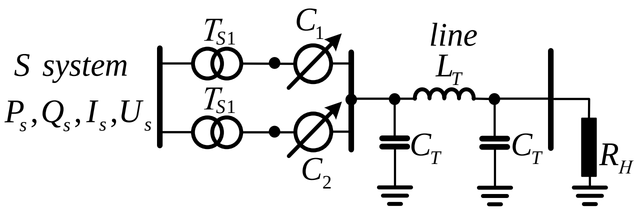


Fig. 22. Scheme of transformer operation for active load through power transmission line 30°

To estimate the frequency transformation quality and power transfer the following power parameters were used: the degree of stability of the transferred active power $\partial P, \%$ and the coefficient of the current harmonic distortions $THD(I), \%$. The results shown in Figs. 23, 24, which are designated using letter 'a' , illustrate the degree of stability of the transferred active power. Letter 'b' stands for the coefficient of the harmonic distortion of the currents. Index 'L' denotes the power supply of the load through the line without an index of the load power supply from the facility busbars.

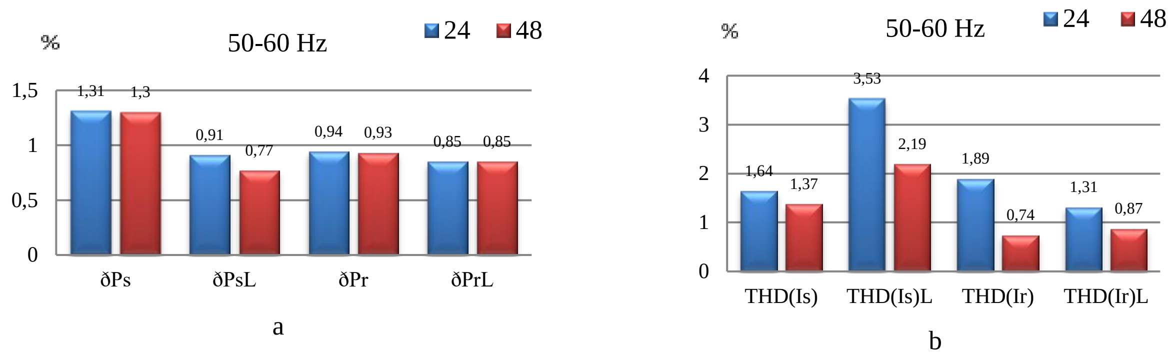


Fig. 23. Hystograms of mode parameters that determine transformation quality during the facility active load operation and at frequency ratio of 50-60 Hz.

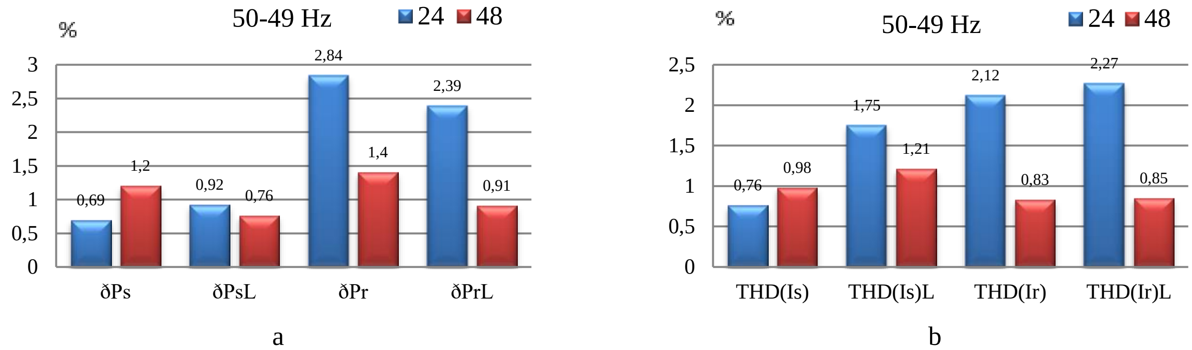


Fig. 24. Hystograms of mode parameters that determine transformation quality during the facility active load operation and at frequency ratio of 50-49 Hz

The hystograms presented justify the expedience of the application of the 48-position sectioning in the engineering of the AC CICM of asynchronous systems with a slip frequency of $\pm 10\,Hz$.

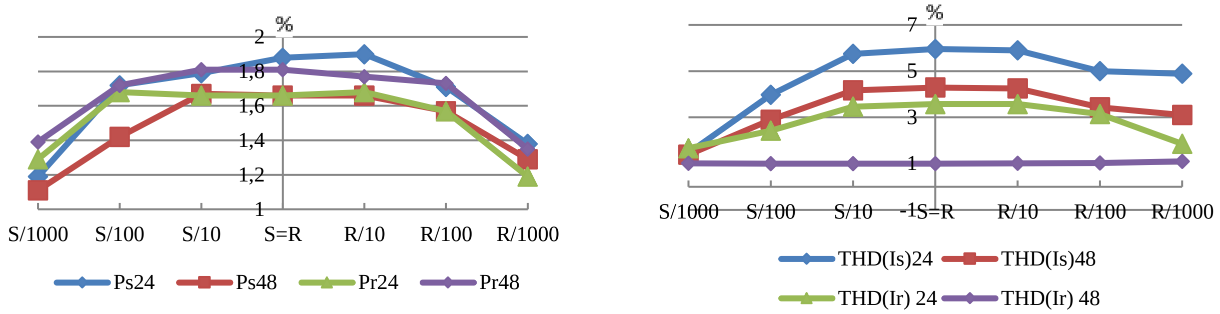


Fig. 25. Graphs of mode parameters with respect to power ratios of transmitting S (50 Hz) and receiving R (60 Hz) systems

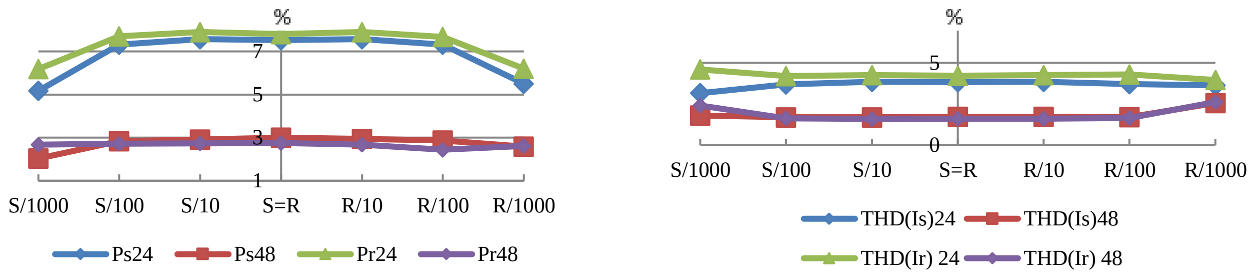


Fig. 26. Graphs of mode parameters with respect to power ratios of transmitting S (50 Hz) and receiving R (49.6 Hz) systems.

The characteristics shown in Figs. 25, 26 attest to the efficiency of the transformer with the 48-position sectioning upon connection of small sources with an unstable operating frequency to the power system.

Then, the inherent operation modes of the CICM with the transformer upon the load-rise and load-drop were studied (Fig. 27), as well as upon a three-phase short circuit fault arising across the busbars of the receiving system (Fig. 28).

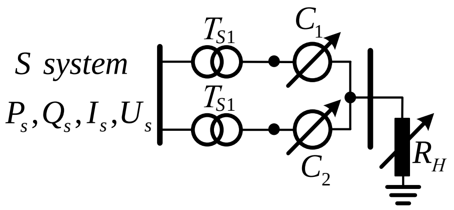


Fig. 27. Experimental scheme at load rise and load drop

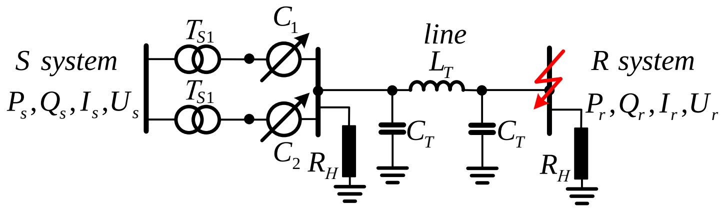


Fig. 28. Experimental scheme during short-circuit fault across busbars of receiving system

The oscillograms of the powers and currents, at the load-rise and load-drop, are shown in Figs. 29—32, the occurrence of a three-phase short circuit fault on the busbars of the receiving system is illustrated in Figs. 33-36.

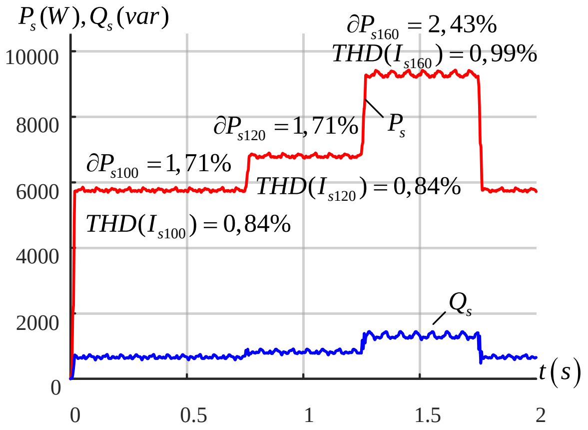


Fig. 29. Transmitting system powers during load rise and load drop

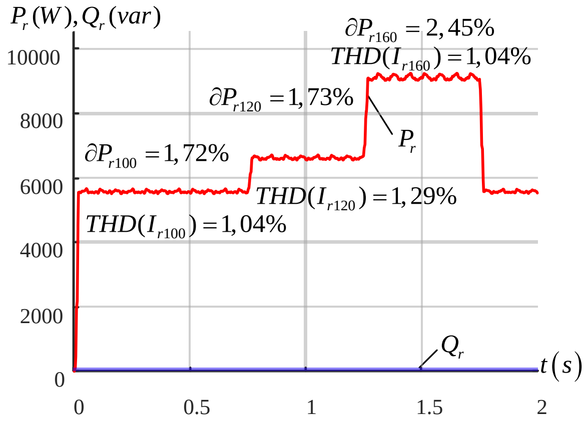


Fig. 30. Receiving system powers during load rise and load drop

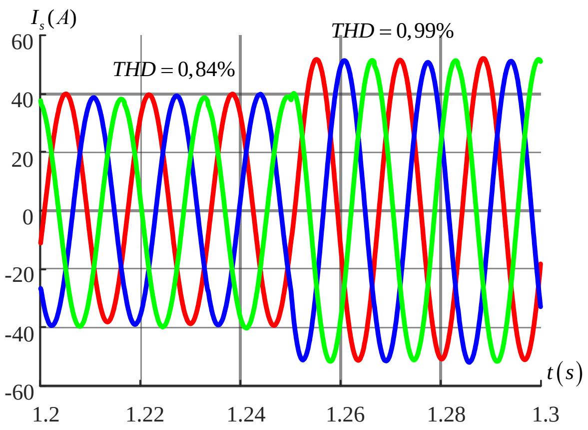


Fig. 31. Transmitting system current during load rise

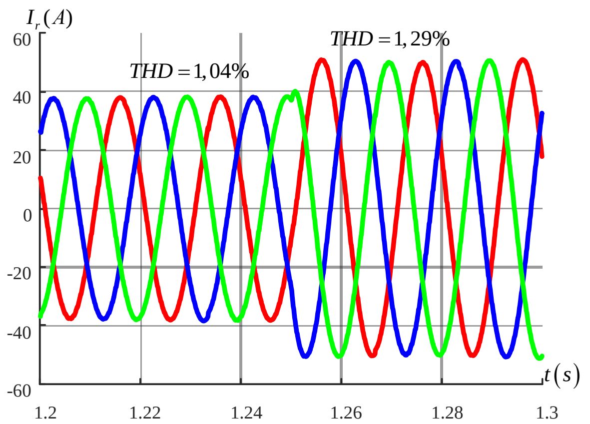


Fig. 32. Receiving system current during load rise

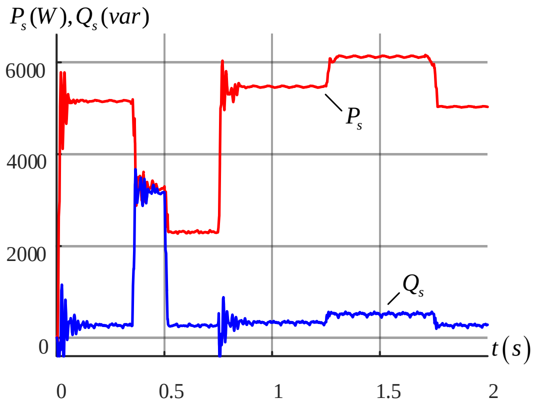


Fig. 33. Transmitting system powers

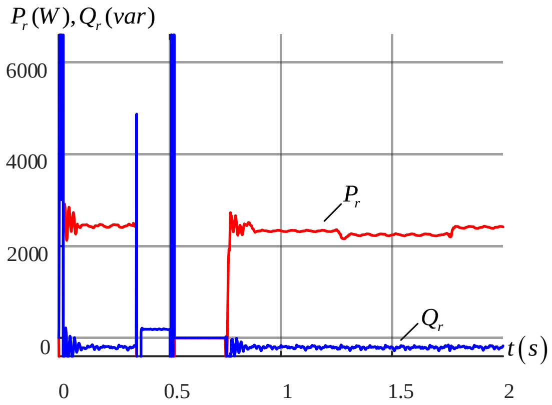


Fig. 34. Receiving system powers

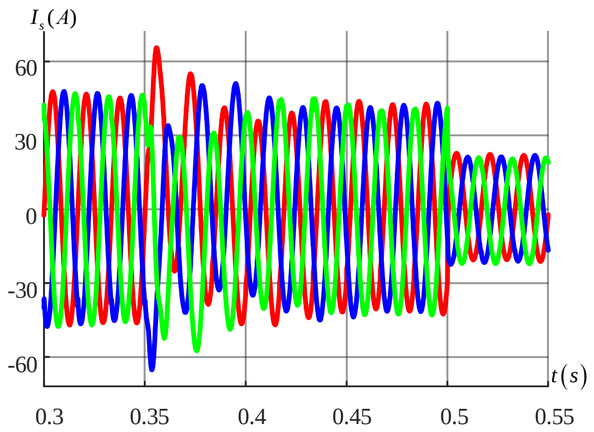


Fig. 35. Transmitting system current at K3 onset and switching off

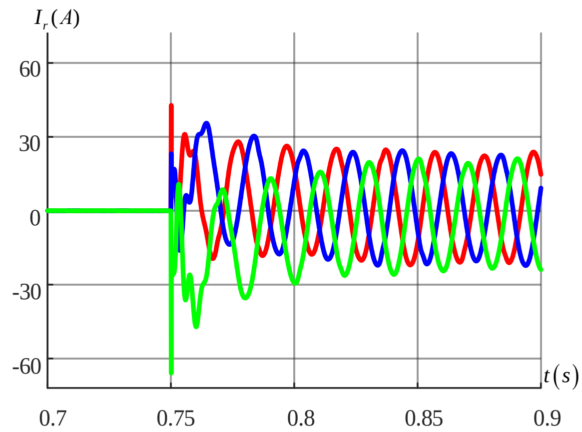


Fig. 36. Receiving system current at CICM reconditioning

The results of the study of the CICM characteristic modes were indicative of the technical efficiency of the proposed schematic variant of the facility from the viewpoint of the frequency transformer response for the disturbance types under consideration.

The analysis carried out points to the expedience of the CICM design based on the frequency transformer with a discreteness of the 'thin' regulation of 2.5°.

<u>Chapter 5</u> developed and studied the CICM on the basis of a ‘hexagon’ scheme transformer, whose principal scheme is shown in Fig. 37.

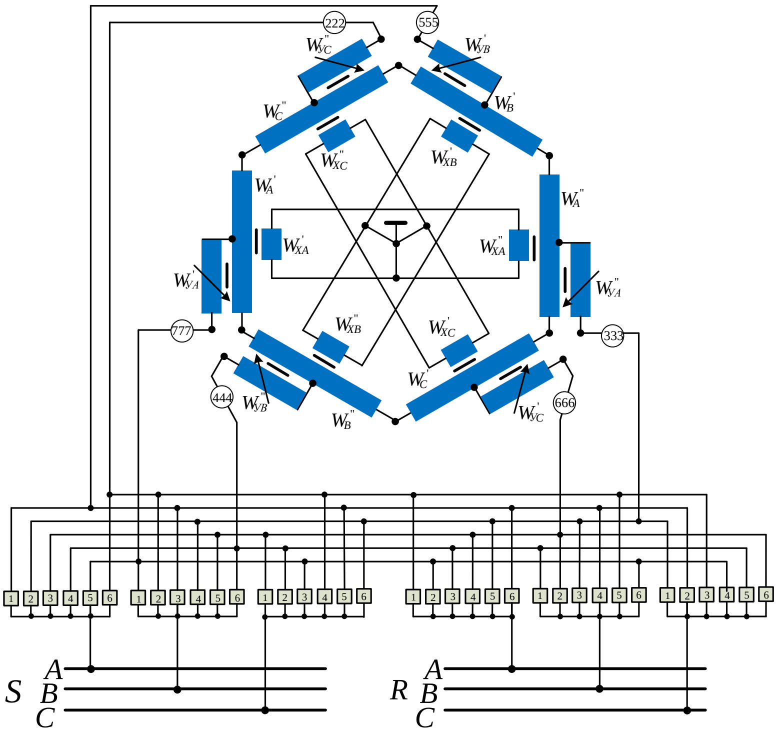
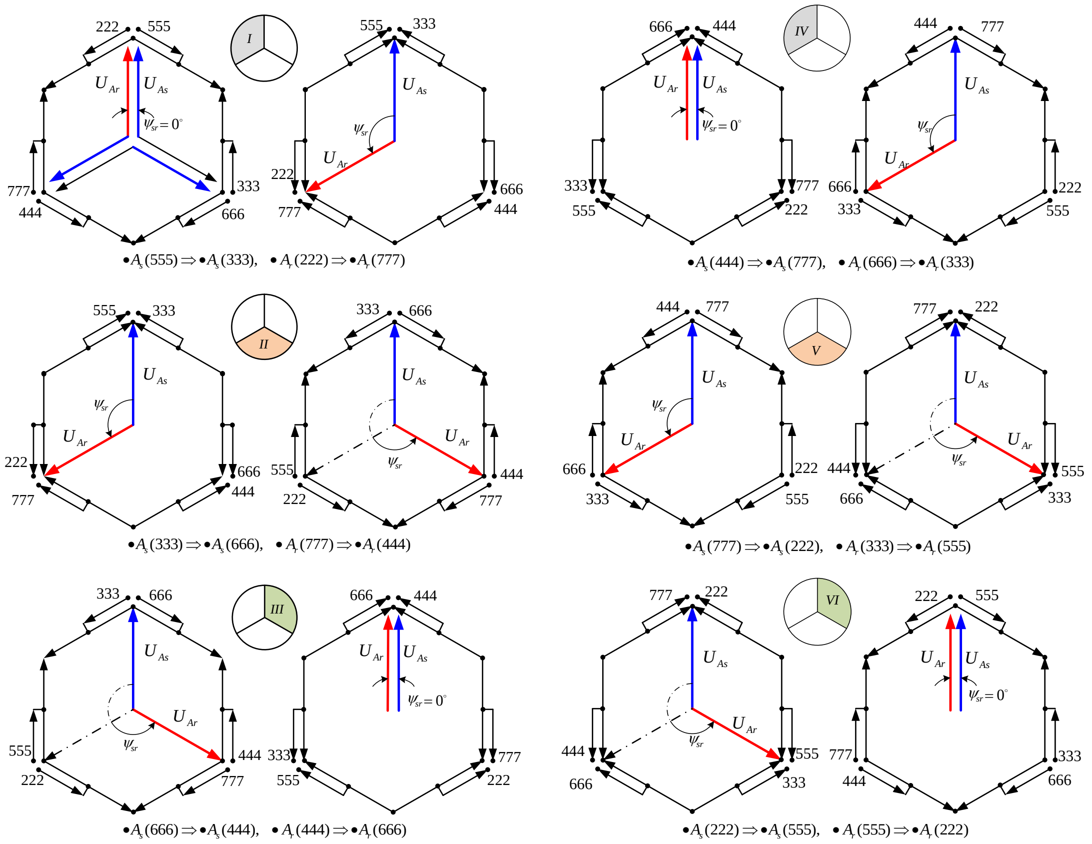


Fig. 37. ‘Hexagon’ principal scheme of static frequency transformer

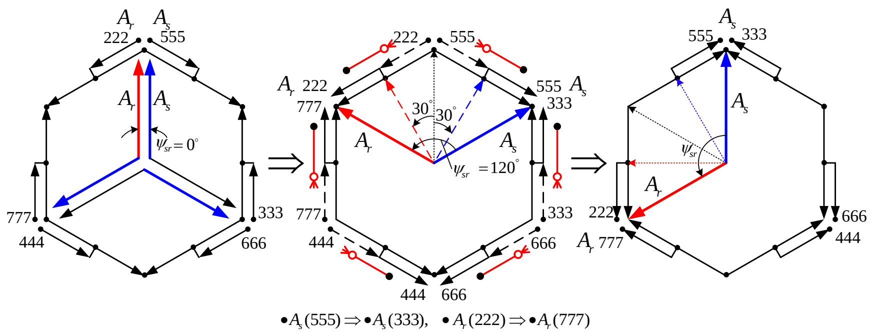
The offered facility also makes it possible to construct the CICM using the principle of a circular phase rotation of the output voltage. In this case, the division of the matching process into the successive operation of the channels is not observed, contrary to the facility described in Chapter 4. The rotation of the output voltage phase occures in accordance with the law of the ‘rough’ control with switching over the operation sectors in 120° (Fig. 38).



a b

Fig. 38. Vector diagram, which explains 'rough' law control

The vector diagram of voltages, which explains the operation of the 'thin' regulation law is presented in Fig. 39.



a b c

Fig. 39. Vector diagram of voltages of the first sector of 'rough' control:

a - is the initial state of the facility; b - is the supply of the phase shift angle; and c - is the phase shift finishing and response of the 'rough' control keys.

The variants of sectioning the windings of the 'thin' regulation and the laws of the key switching over for 24 and 48 steps of regulation are shown in Figs. 17—20.

To study the mode parameters of the static frequency transformer performed using the 'hexagon' scheme, the calculation experiments for two laws of the 'thin' regulation were carried out (Figs. 40, 41).

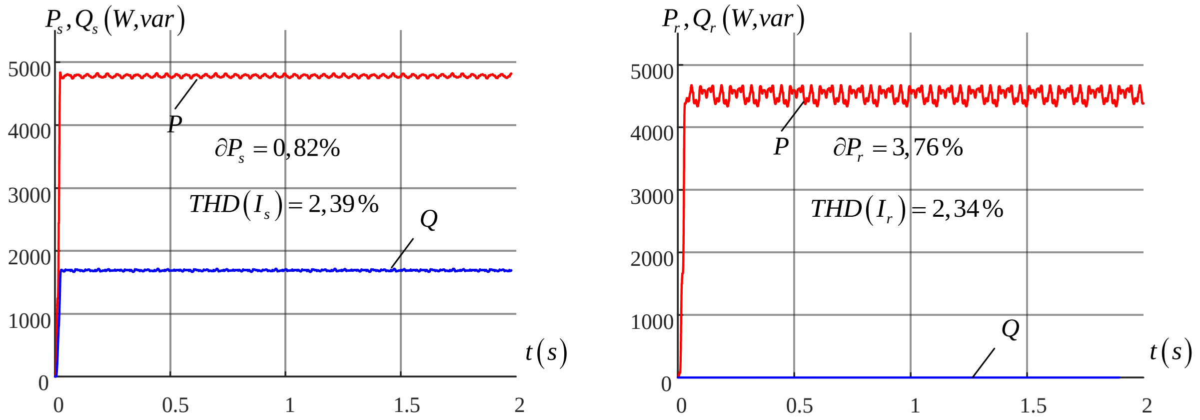


Fig. 40. Powers at transmitting and receiving systems for 24 positional sectioning

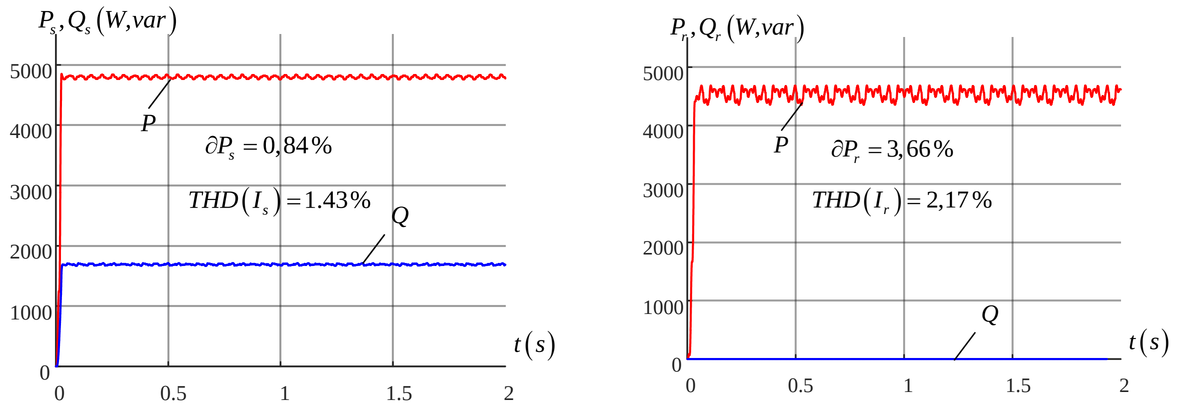


Fig. 41. Powers at transmitting and receiving systems for 48 positional sectioning

To study the possibility of improvement for the facility operation characteristics the multifunctional principle was offered to be used during the CICM scheme plotting. For this purpose, matching transformers were developed (Figs. 42, 43) to ensure the correct operation of the facility upon various amount of the channels; and the initial positions of the power keys of the 'thin' regulation laws were matched during the facility operation in the multi-channel mode.

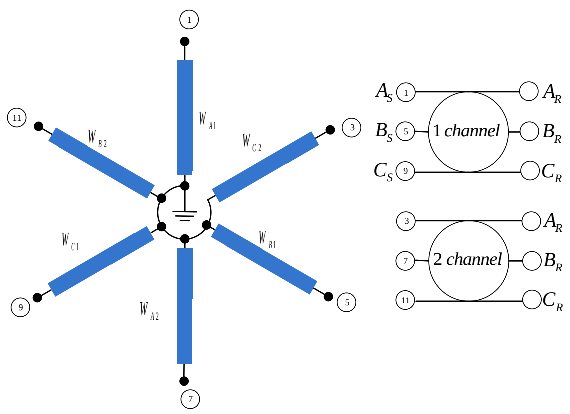


Fig. 42. Matching transformer for two-channel converter

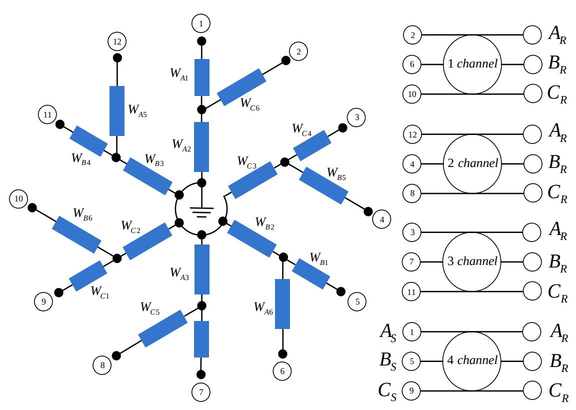


Fig. 43. Matching transformer for four-channel converter

In order to estimate the quality of transformation at the facility with a multi-channel scheme the transformer operation was studied in two- and four- channel modes (Figs. 44, 45) with the 24 and 48 position sectioning. The levels of the transferred power were 100, 65 and 30% from the facility nominal power. The results of the examination are shown as hystograms in Figs. 46, 47.

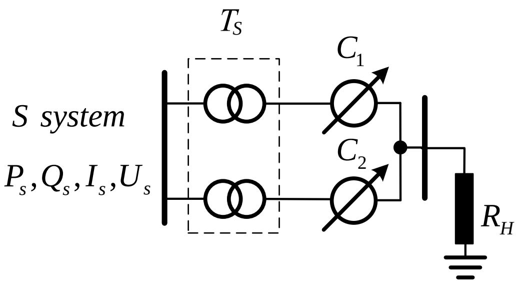


Fig. 44. Experimental scheme for two-channel transformer

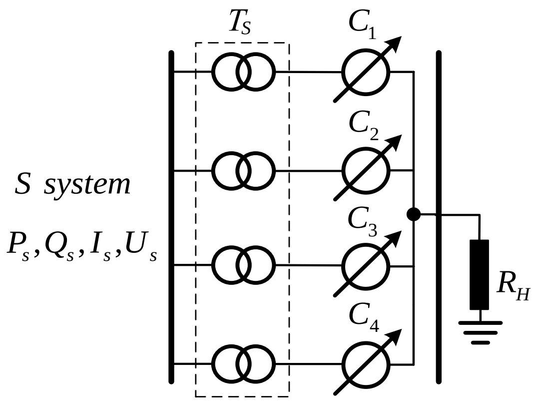


Fig. 45. Experimental scheme for four-channel transformer

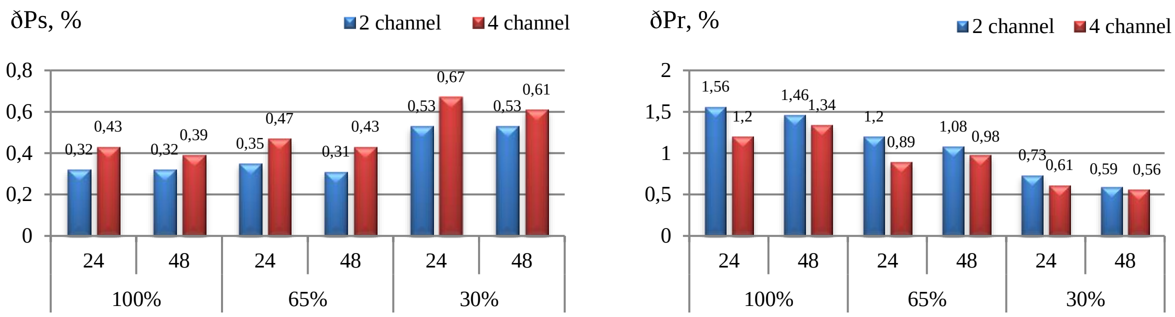


Fig. 46. Hystograms of stability degrees of transmitted power at transmitting (ðPs) and receiving (ðPr) systems

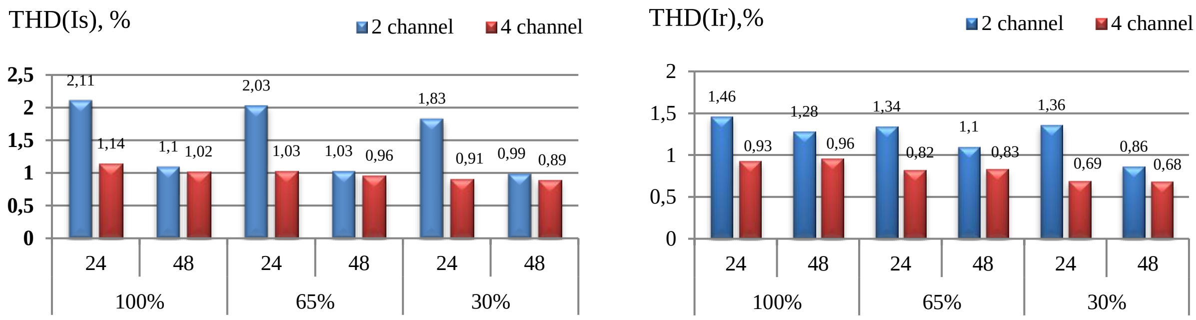


Fig. 47. Hystograms of coefficients of current harmonic distortions at transmitting ($THD(I_s)$) and receiving ($THD(I_r)$) systems

The comparative analysis of the hystograms obtained revealed the advantage of the four-channel scheme of transformation being combined with the 48 positional sectioning of the control winding.

The study of the inherent operation modes of the CICM facility was performed at a different number of channels simultaneously operating, as wellas at arising the three-phase short-circuit factor across the busbars of the transmitting system.

The results of the experiments with different amount of operating channels during the facility load operation are shown in Figs. 48, 49 and those, using a 300 -power transmission line, in Figs. 50, 51.

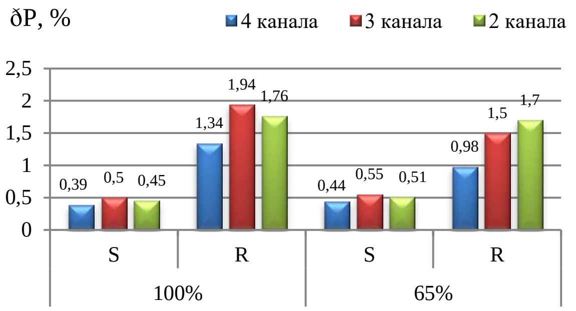


Fig. 48. Hystogram of stability degrees of transmitted power without power transmission line

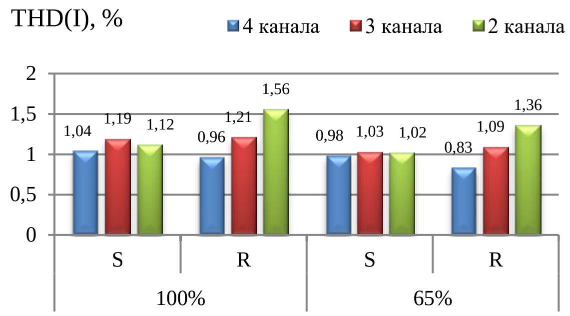


Fig. 49. Hystogram of coefficients of current harmonic distortions without power transmission line

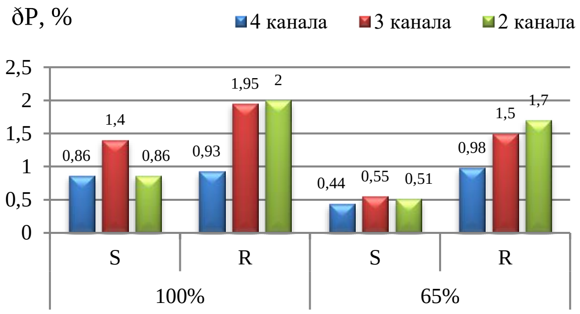


Fig. 50. Hystogram of stability degrees of transmitted power with power transmission line

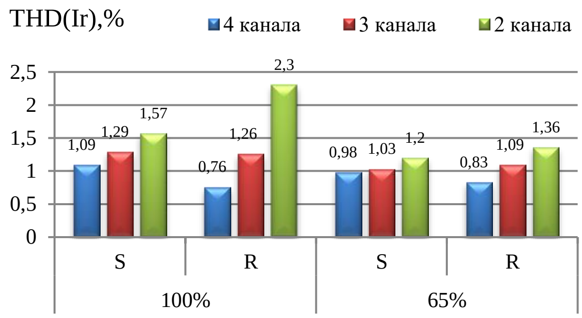


Fig. 51. Hystogram of coefficients of current harmonic distortions with power transmission line

The hystograms shown in Figs. 48—51 are indicative of the facility, which makes it possible to maintain the mode indices of ($\partial P,\%$ and $THD\left(I\right),\%$) in permissible limits at a various number of the operating channels. The plotted hystograms allow as well making the conclusion on the possibility of creation the standardized sample of the transformer and ensure its serial production, which will decrease the cost of the transformers of the kind.

The power oscillograms inherent to the facility operation during the origin of the three-phase short-circuit fault across the busbars of the transmitting system (Fig. 52), are shown in Figs. 53—56.

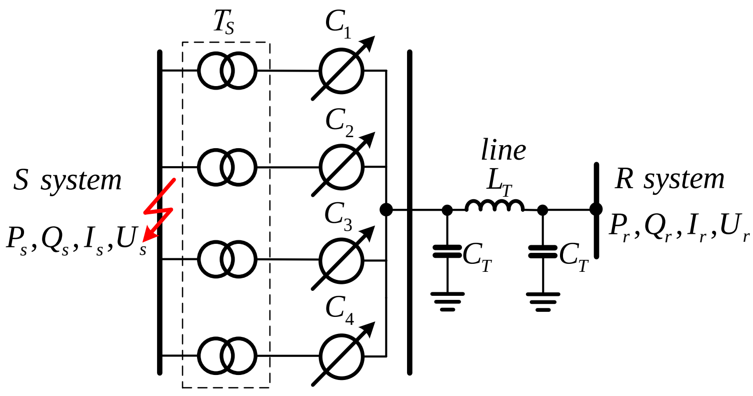


Fig. 52. Experimental scheme performed at SC on busbars of transmitting system

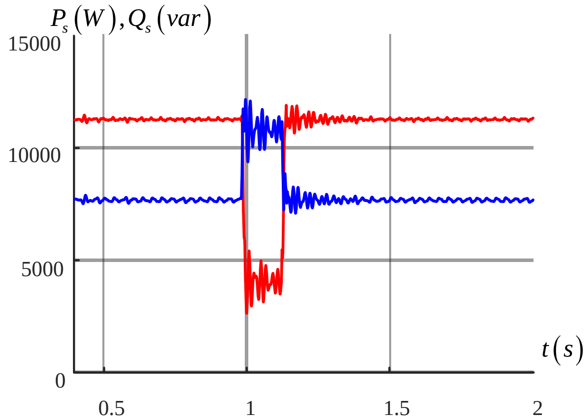


Fig. 53. Transmitting system powers

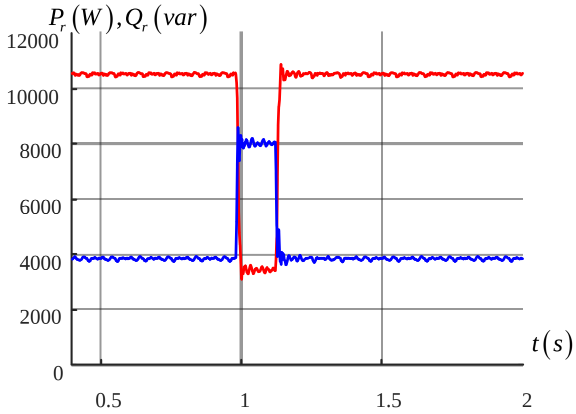


Fig. 54. Receiving system powers

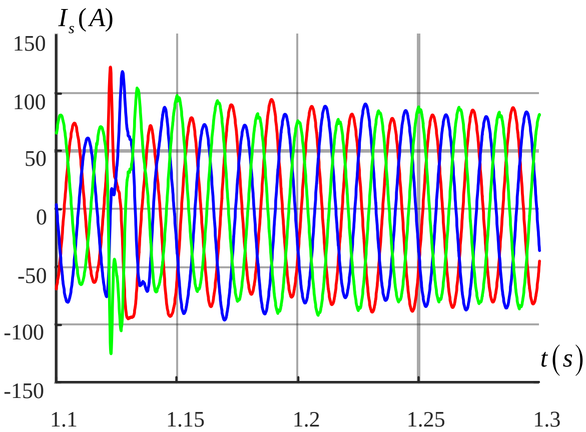


Fig. 55. Transmitting system current at short-circuit fault switching off

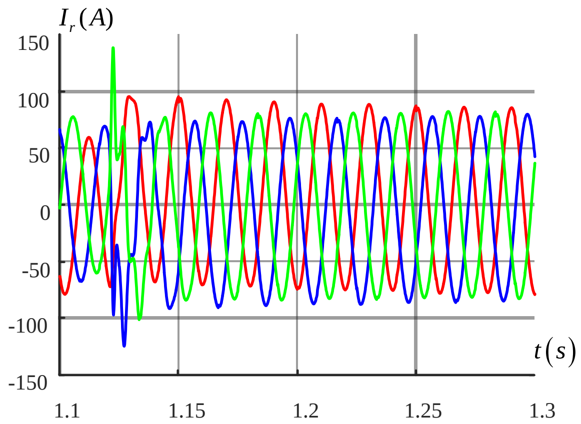


Fig. 56. Receiving system current at short-circuit fault switching off

The results of the study of the inherent modes of the facility operation showed that irrespective of the place of the disturbance and of the number of the operating channels of the facility, time for the mode reconditioning after the removal of the disturbance is up to 0.2 s, which is relevant to the characteristics of the rotary frequency changers.

The research performed indicates that the multi-channel variant of the facility makes it possible to: construct the alternating current CICM with no filter compensating devices; improve the quality of transformation due to the application of the multi-channel principle; and ensure interchangeability of individual elements of the facility under study, increasing thus the reliability of the alternating current CICM.

General conclusions and recommendations. This dissertation paper generalizes the existing methods for the CICM development. It enables to solve the scientific and engineering issues for the alternating current CICM organization based on the proposed schematic variants of the static frequency transformers.

The major theoretical and calculation-experimental results of this work are as follows:

1. The studies of the existing methods for the alternating current CICM organization showed that the elaborated device VFT (firm General Electrics), as well as the theoretically and experimentally studied sample of the AS EMFT does not ensure the matching of two asynchronously operating power systems, whose frequency slip is over ±3 Hz.

2. The mathematical models of the transformation facilities are offered based on the constant current sources and on the static transformers, which prove the possibility of the AC CICM implementation between two power systems with different standards of frequency.

3. The electrical schemes and structural-simulation models of the facilities are developed for the purpose of experimental researches in the static and dynamic states of the operation of transformers, which allow estimation of the transformation process quality.

4. The laws of control by the frequency transformer were determined based on the constant current sources, which make it possible to ensure the preset value and the direction of the power transferred in the process of frequency matching by means of division of the conjugated conductivities into the elementary modules.

5. It is shown that the frequency transformer based on the constant current sources allows ensuring the CICM with different frequency standards. The use of harmonic filters and dampers, in this case, allowed reduction in the coefficient of harmonic distortions at the transmitting system from 7.02 to 4%, whereas at the receiving system it was reduced from 8.31 to 5.07%, which satisfies the requirements of the IEEE-519 standard.

6. The schematic variants of the static frequency transformers of the converter type were developed, which realize the principle of circular rotation of the phase of the output voltage. The laws of the ‘rough’ and ‘thin’ control, which made it possible to realize the transformation process at a various degree of discreteness.

7. It was shown that the proposed schematic variants of the static transformers with a circular transformation of the output voltage phase, and the law of control with discreteness of

the switching step of $2,5^o$, allow engineering the AC CICM of the asynchronously operating power systems, whose frequency slip is in the range of ± 10 Hz, without the use of harmonic filters and dampers.

8. It was established that upon the deviations from the network normal mode of operation, such as load rise and load drop or a disturbance induced by the current short-circuit fault, the facility under study reconditions the mode parameters up to the values relevant to the normal operation mode during the time of about 0.2 s. The reconditioning time is independent of the distance from the fault location.

9. The application efficiency of the multichannel principle on the static transformer converters was proved. The said principle ensures reservation of the facility channels, performance of current and complete repairs, approbation of operation of each separate channel without malfunction of the CICM operation, which can be positive for the security of operation of the AC CICM of two asynchronous power systems.

10. The results of the study showed that the proposed types of the static frequency transformers structurally remind of and solve most of the issues inherent for the ‘DC Link’ or ‘Back-to-Back DC Link’. Thus, by analogy, the offered facilities can be referred to as an ‘Alternating Current Link’ or ‘Back-to-Back AC Link’.

The results of the research are supported by five major publications and were reported at three conferences.

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ABSTRACT

The author – Danila Kaloshin. **The title** – *Study of Flexible Interconnecting Mains Based on Transformer Frequency Converters*. Dissertation for awarding the doctorate degree in technical sciences, speciality *221.01. Power systems and technologies.*

Structure of the work: the dissertation includes introduction; five chapters; conclusions and recommendations; references, which contain 137 source and 107 appendices; 170 pages of the main text; 6 tables and 100 figures; 6 scientific works are published based on the research results.

Keywords: rotary frequency changer, asynchronous controlled intersystem connection, Interphase Power Controller (IPC), frequency transformation, multi-module frequency transformer, static transformer frequency converter.

Field of study - technical sciences. **Target of dissertation** consists of the persuance of theoretic and calculation-experimental researches of the alternating current controlled interconnecting mains (AC CICM) based on the static transformer frequency converters.

Dissertation tasks: include the development of mathematical models of the facilities based on constant current sources and static transformers with a circular transformation of the output voltage phase; elaboration of the electric schemes, as well as the laws of control by the operating modes of the facility types under consideration; study of the facilities in the stages of static and dynamic states; determination of expedience of the future studies in the development of the AC CICM based on static transformer frequency converters.

Scientific novelty of the work: includes the mathematical models developed on the basis of the constant current sources and static transformers with a circular transformation of the output voltage phase; the electrical schemes of the facilities developed based on the constant current sources performed according to ‘zig-zag’ and ‘hexagon’ schemes; the laws of control by the operating modes of the facilities under study to organize the AC CICM.

Scientific problem solved: as the result of the study performed, the possibility is shown to solve the scientific and engineering problems of organization the AC CICM based on the proposed schematic variants of the facilities.

Theoretical importance. The research performed can serve as the basis for the deeper and more detailed study of the AC CICM using the static transformer frequency converters.

Application relevance of the work: realization of static frequency transformers will make it possible to ensure a simpler, from the viewpoint of organization, the AC CICM without the application of an intermediate link of the DC transformation.

Implementation of scientific results: the research results can be used in the process of theoretical and experimental studies, design and experimental works and technological engineering, as well as the development of the control devices and automated modes of operation for the devices of this kind.

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STUDY OF FLEXIBLE INTERCONNECTING MAINS BASED ON TRANSFORMER FREQUENCY CONVERTERS

221.01 – POWER SYSTEMS AND TECHNOLOGIES

Abstract of a dissertation for a scientific degree
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