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THE MODELING OF THE FREQUENCY CONVERTER MODES ON THE BASIS OF PHASE-SHIFTING TRANSFORMER

BY

MIHAI TÎRŞU*, LEV KALININ, DMITRY ZAITEV and SVEATOSLAV POSTORONCA

Institute of Power Engineering of Academy of Sciences of Moldova, Chişinău

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Abstract. The problem of mutual exchange of energy between the asynchronous power systems is becoming more relevant with increasing of energy production from renewable sources. The well-known means of solving this problem are the widely applied HVDCT (High Voltage Direct Current Transmissions) and VFT (Variable Frequency Transformers). As an alternative, it may be proposed the device operating on the principle of PST (Phase Shifting Transformer). The article considers a variant of such device which is applied in conjunction with (Interphase Power Controller (IPC). The article gives the description of schematic diagram of device, formulates the control strategy of frequency conversion and also provides some characteristics that illustrate the conversion procedure.

Key words: energy exchange; Interphase Power Controller; phase shifting transformer; Variable Frequency Transformer.

1. Introduction

A further increase in electricity production is inevitably associated with the development and increase of complexity of interconnected electric power systems, which makes it difficult to control the flow of active and reactive power. There is an increasing number of elements with reduced control, such as high capacity condensation and nuclear power plants, intended to operate in the basic mode, appear large energy consumers with sharply-variables load curve.

*Corresponding author : *e-mail*: tirsu.mihai@gmail.com

Thereby, frequently it is not enough to use traditional management facilities, based on the generation sources regulation. The use of phase-shifting transformers (PST) as stand-alone control devices gain more and more application range (Brochu *et al.*, 2006; Kalinin *et al.*,2008; Pelletier *et al.*,1996). The combination of PST with reactive elements (Kalinin *et al.*, 2010; Kalinin *et al.*, 2007) lead to a separate branch of FACTS family called IPC - controllers (Inter-phase Power Controllers).

One of the prevailing trends in this area is the development and formation of static controlled electrical connections between asynchronous power systems that are called Back-to-Back (B2B) connections. One disadvantage of these devices are the dual-energy conversion (rectification and inversion), and the related additional losses of electricity. Recently, for these purposes are getting application devices of VFT (Variable Frequency Transformers) type (Bakhsh *et al.*, 2013; Bakhsh *et al.*, 2011). These devices ensure a direct energy conversion, however possess a mechanical inertness, additional consumption of electricity on mechanical manipulations with VFT rotors and comprise friction electrical contacts that require constant maintenance during operation which reduce the reliability of such devices.

This work treats the version of the device of similar purpose, which can be taken as a working model for the implementation of the principle of direct frequency conversion (Kalinin *et al.*, 2011), not associated with power double-conversion and without the shortcomings characteristic for VFT. Such a device can be conditionally called ACL "Alternating Current Link".

2. General Feature of the Device

The device represents itself a power transformer with windings sectioned and switched by the switch operation, engineered on the basis of power electronics means. The circuit diagram is shown in Fig.1.

Three-phase system of input voltages is applied to the terminals U_s, aU_s, a^2U_s and the system of output voltages is collected from the terminals U_r, aU_r, a^2U_r. The windings of the transformer, marked with the index q perform the function of longitudinal control, while the windings with the index p, in delta connection – the function of –transversal operation. The windings of the longitudinal control are divided into two identical parts $k_qW_q/2$. The input currents are terminals I_s, aI_s, a^2I_s, and output I_r, aI_r, a^2I_r. Currents circulating in the windings, connected in a delta connection are respectively I_p, aI_p, a^2I_p.

The switching of operating windings sections provides a stepwise variation of the phase shift angle Ψ of the output voltage with respect to the applied voltage in the range from 0 to 360 degrees. The state of each winding is characterized by coefficients k_q and k_p, which define the number of operating sections in each winding at each moment of time during the control.

Smoothness of regulation depends on the number of sections of the operation winding (for the device in question is accepted m = 15). In this case the diagram of execution of the operation winding, shown in Fig. 2, allows getting 30 steps, taking into account the reversal.

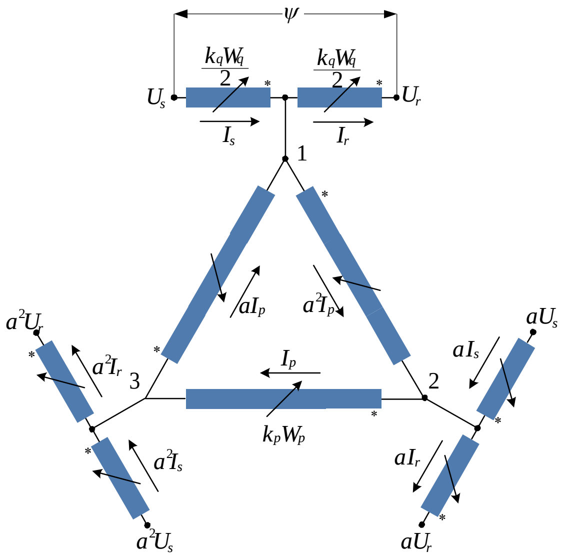

Fig. 1 The diagram of the device.

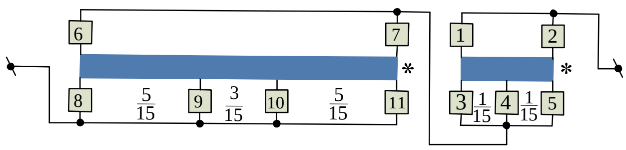

Fig. 2 – The view of operation winding.

Taking into account the above mentioned considerations, the equation of ampere-turns of phase-shifting transformer takes the form:

$$I_s \frac{k_q W_q}{2} + I_r \frac{k_q W_q}{2} = I_p k_p W_p \,, \tag{1}$$

where

$$I_p = \frac{1}{2} \cdot \frac{k_q}{k_p} \cdot \frac{W_q}{W_p} \left(I_s + I_r \right). \tag{2}$$

On the other hand, for the node 1 one can write:

$$I_s + aI_p = I_r + a^2 I_p \,, \tag{3}$$

where

$$I_p = j \cdot \frac{I_s - I_r}{\sqrt{3}} \,. \tag{4}$$

Accepting the condition:

$$\frac{W_q}{W_p} = \frac{2}{\sqrt{3}}, \tag{5}$$

one can obtain

$$I_r = \frac{j - \dfrac{k_q}{k_p}}{j + \dfrac{k_q}{k_p}} \cdot I_s = \dot{K} I_s \ . \tag{6}$$

The value $\dot{K}$ is the complex factor of phase conversion of the cycle convertor.

It should be noted that the phase transformation in this case is carried out at a constant phase voltage at the output in the absence of load current, wherein in the control process the end of each phase vector of output voltage is moved along a circular arc.

3. The Strategy of Control

To study the modes of energy transmission between the asynchronously operating power systems in a Matlab-Simulink environment, a model of the cycle convertor has been created. The model is designed to phase voltage of 230 V and rated current of 24 A.

The model comprises following blocks:

1. the transmitting and receiving power systems (in the form of the voltage sources of infinite power with the sine form of voltage);
2. the transformer blocks;
3. the blocks for measurement and analysis of the device mode parameters;
4. the blocks of commutation and control systems.

The whole operation area is conventionally divided into two equal parts (see. Fig. 3):

a) the first part covers the limits from 270º *via* 0º to 90º;

b) the second part answer to the area from 90º *via* 180º to 270º.

The realization of the mode for the first part is achieved when $k_p = 1 =$ $=$ const. and regulation of k_q is carried out within the range $k_q = \text{var}(-1 \div 0 \div 1)$.

Wherein, the conversion mode of current and voltage arising from (6) can be presented as follows:

$$\left.\begin{matrix} I_r \\ U_r \end{matrix}\right\} = \frac{1 + jk_q}{1 - jk_q} \cdot \left\{\begin{matrix} I_s \\ U_s \end{matrix}\right. . \tag{7}$$

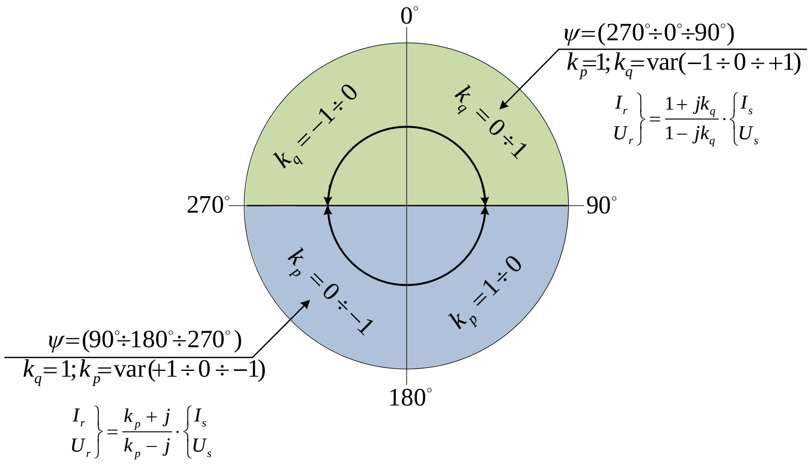

Fig. 3 – The strategy of control.

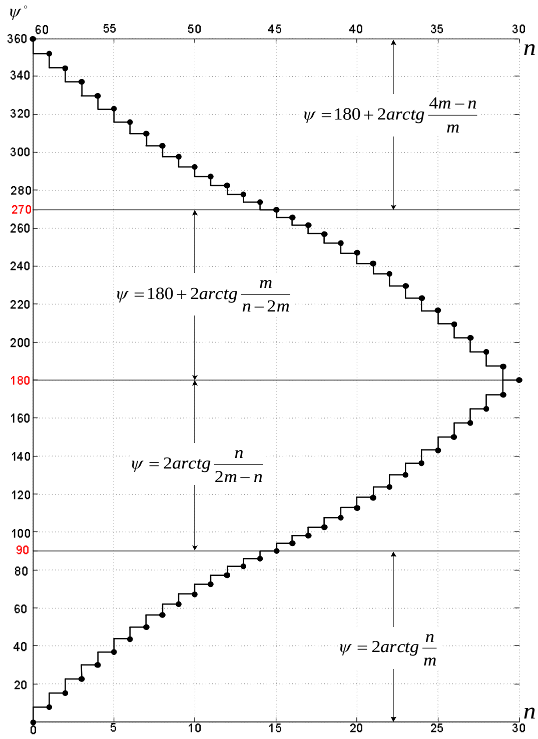

Fig. 4 – The dependence of phase shifting angle ψ on the switching number.

The realization of the mode for the second part is achieved when $k_q = 1 =$ = const. and regulation of k_p is carried out within the range k_p = var(–1 ÷ 0 ÷ 1).

Wherein, the conversion mode of current and voltage arising from (6) can be presented as follows:

$$\left.\begin{array}{l} I_r \\ U_r \end{array}\right\} = \frac{k_p + j}{k_p - j} \cdot \left\{\begin{array}{l} I_s \\ U_s \end{array}\right. . \tag{8}$$

The entire area of phase shifting from 0º to 360º is divided in n = 60 positions.

The control procedure is complicated due to the fact that uniform sectioning of operating windings, as resulting from the technical requirements to the adjustor, leads to non uniform increment by one stage of phase shift angle between the input and output voltages of the device. This peculiarity is caused by the lack of linearity of change of phase shifting angle Ψ with the change of position number $n = 1 \div 60$, that follows from the examination of Fig. 4.

This fact demonstrates the need for further improvement of the proposed principle of conversion.

4. The Results of Modeling

The results of modeling of the process of free power change between asynchronous power systems at frequency 50 Hz and 50.2 Hz without any control, are showed in the Fig. 5

Such a difference between the frequencies is chosen according to the standard requirements, which define the value Δf = 0.2 Hz as limit for the initiation of automatic frequency unloading operations.

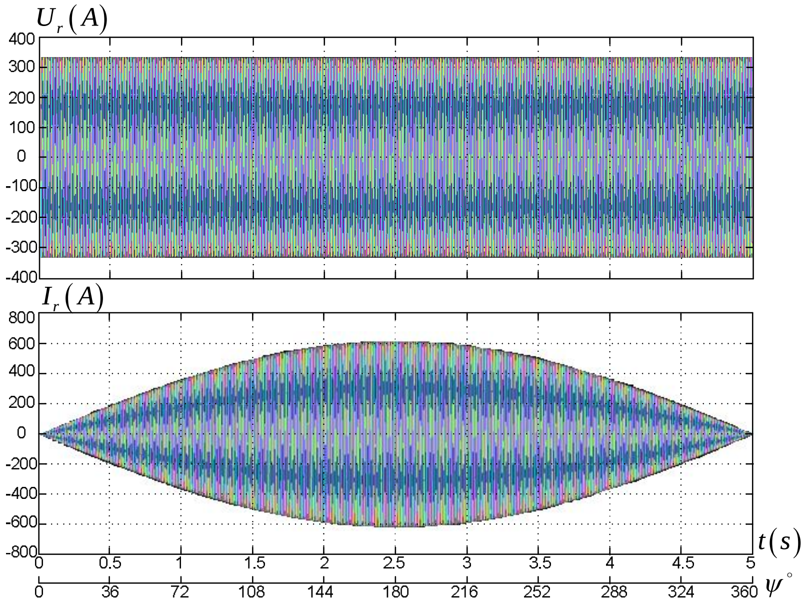

Fig. 5 – The envelopes of current and voltage in the receiver system operating at a frequency 50.2 Hz.

Fig. 5 shows enveloping curves of current (I_r) and voltage (U_r) at the receiving system under this condition. The maximum value of current occurs at the moment when voltages of the systems are in opposite phase that correspond to the time t = 2.5 s. The greatest value of current I_r is 20 times higher than the nominal one of the model and limited by the leakage reactance of transformers only.

For comparison during this experiment it has been used a simple diagram of Interphase Power Controller (IPC) proposed by Charles Steinmetz. Herewith the rated current of IPC is selected equal to the nominal current of phase-shifting transformer. As it can be seen from a consideration of waveforms presented in Fig. 6, the use of IPC leads to restriction of current I_r to the nominal value regardless of the angle Ψ.

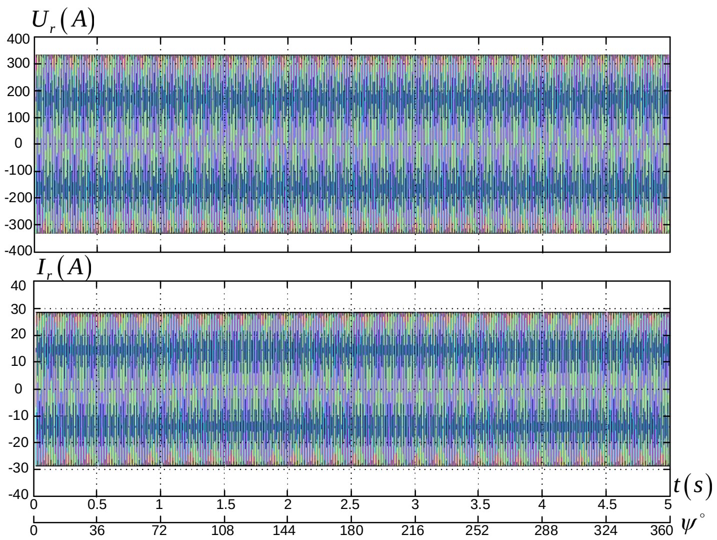

Fig.6. The envelopes of voltage U_s and current I_s by using IPC.

In Fig. 7 are given the waveforms of current and voltage under the control of the mode of power transmission in accordance with accepted strategy. In this rated experiment, the IPC technology has also been applied. It can be seen that the power exchange is provided at the nominal values of the parameters of the regime. A certain modulation of load currents is caused by nonlinearity of the phase shift angle Ψ with variation of the step number shown in Fig. 4.

Distortion factor of load currents corresponding to this experiment constitutes 0.27% as it follows from the analysis presented in Fig. 8.

Fig. 9 illustrates the features characterizing the process of transfer of active and reactive power between the asynchronously operating systems under forced control with the fixed difference of frequency 0.2Hz. From an examination of the waveform it can be seen that the index of oscillation of the

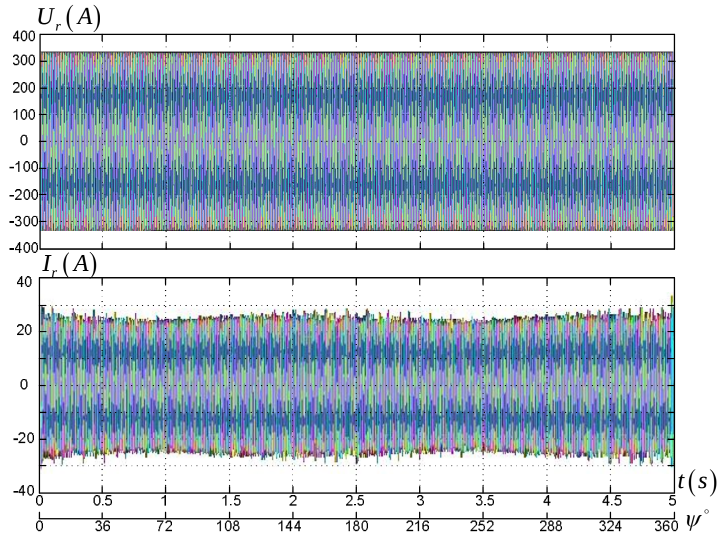

Fig. 7 – The envelopes of voltage U_s and current I_s on the side of the receiving system under forced control mode.

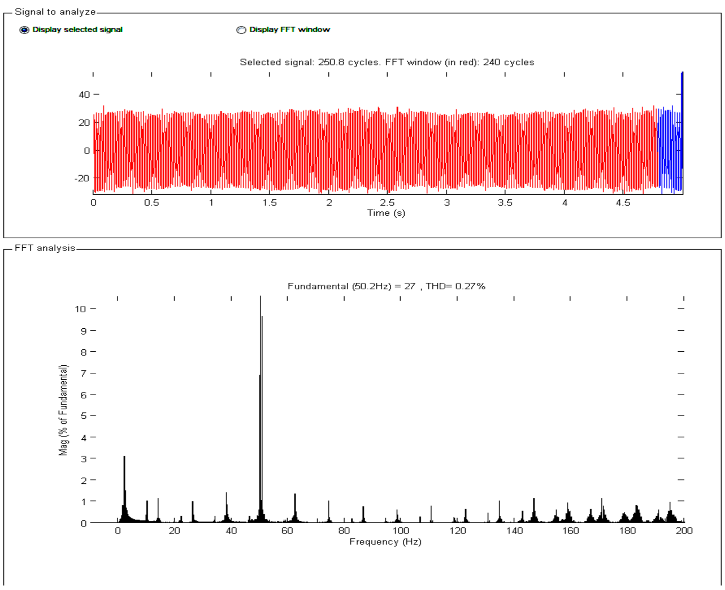

Fig. 8 – Harmonic analysis of load currents.

active power is about 5%, due to the nonlinear relationship of the phase shift angle Ψ regarding to the control step position. This does not always meet the requirements of the operational regulations for electric power systems. Additionally attention is drawn to a “toothed” form of reactive power characteristic. This feature of characteristic is due to the use of IPC, the degree of its manifestations is sharply reduced with increasing frequency difference between conjugated power systems. It should be noted that the shown in Fig. 9 characteristics appear here only as an illustration of the operability of the described principle.

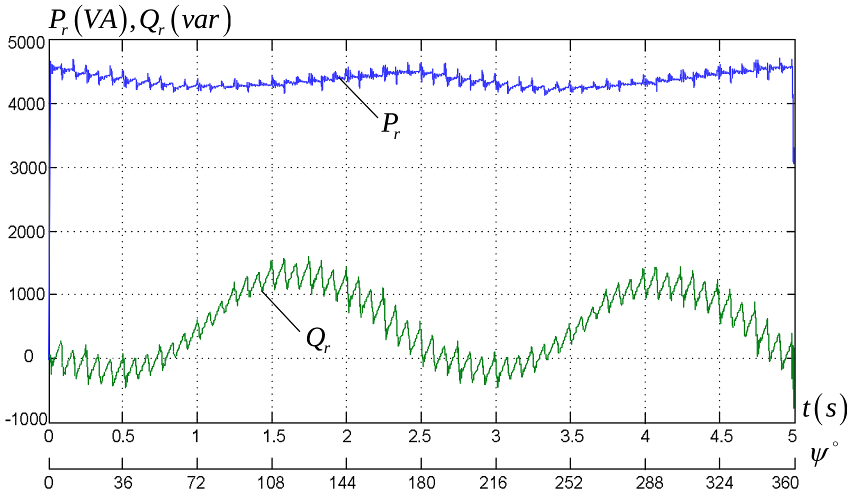

Fig. 9 – The nature of the changes of transmitted power under forced control.

Further improvement of presented principle concerning the operation of AC Link may be achieved by eliminating of both indicated drawbacks related to nonlinearity and the value of the switching step. Fig. 10 shows the schematic diagram of device that allows the solution for both specified tasks by using a block of coarse adjustment and a block of fine tuning. The block of coarse adjustment is composed by three-phase power electronic switches1-6. The block of fine tuning is represented by modified phase-shifting transformer based on the diagram shown in Fig.1 in which the delta windings are the conventional non-adjustable elements. The control range of phase - shifting transformer is $\Psi = \pm 30^{o}$.

Rated capacity of such devices is determined as follows:

$$S_{PST} = 2\sin\frac{\psi}{2}U_s I_s\,, \tag{9}$$

where: U_sI_s is the full load capacity of power transmission.

Thereby, rated capacity of examined phase-shifting transformer in is:

$$S_{\mathrm{PST}} = 2\sin\frac{30^\circ}{2}U_s I_s = 0.518 U_s I_s\,. \tag{10}$$

This is only 0.518 of throughput capacity of transmission.

The block of coarse adjustment provides the formation of six sectors (each consist of 60º), in the boundaries of which operates a phase-shifting transformer. This transformer provides the fine tuning step switch of control

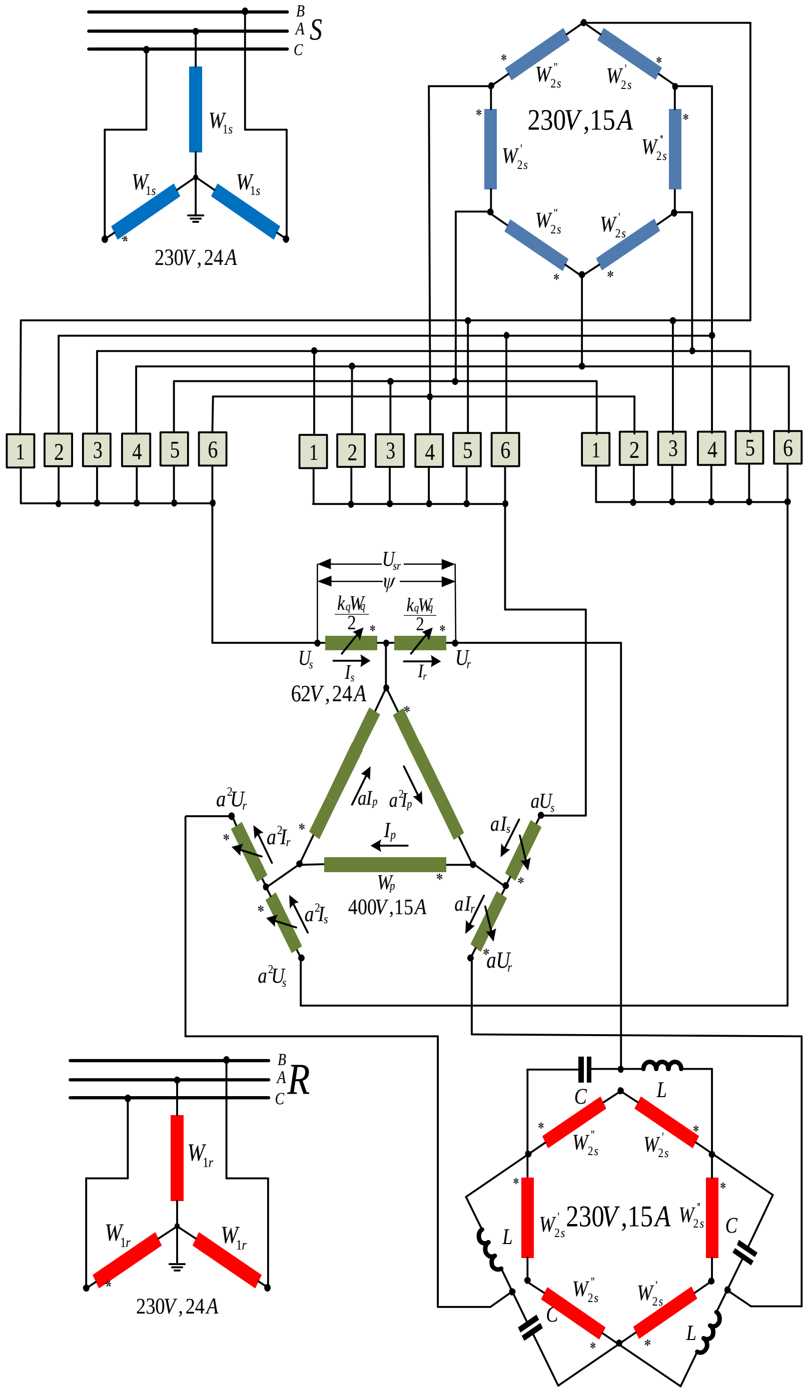

Fig. 10 – Schematic diagram of modified cycle converter.

windings (shown in Fig. 2) with readability one stage of 2º. Since the one block of a coarse adjustment is divided into 30 steps then the entire circumference consist of the 180 possible fixed steps of the regulated phase shift of output voltage. The total use of these measures has significantly improves the quality of frequency conversion process..

The switching diagram presented at the Fig. 11 describes the sequence of control operations to ensure interaction between the blocks of coarse and fine adjustment. Each of existing positions (total number of 180 pieces) has its own operational code. The problem of control the frequency conversion mode, as well as the problem of control the level of transmitted power, is reduced to the need to determine the sequence of the switching operations and the periods of duration for each working position. In the context of the current state of technical means of automatic control this kind of problems are elementary.

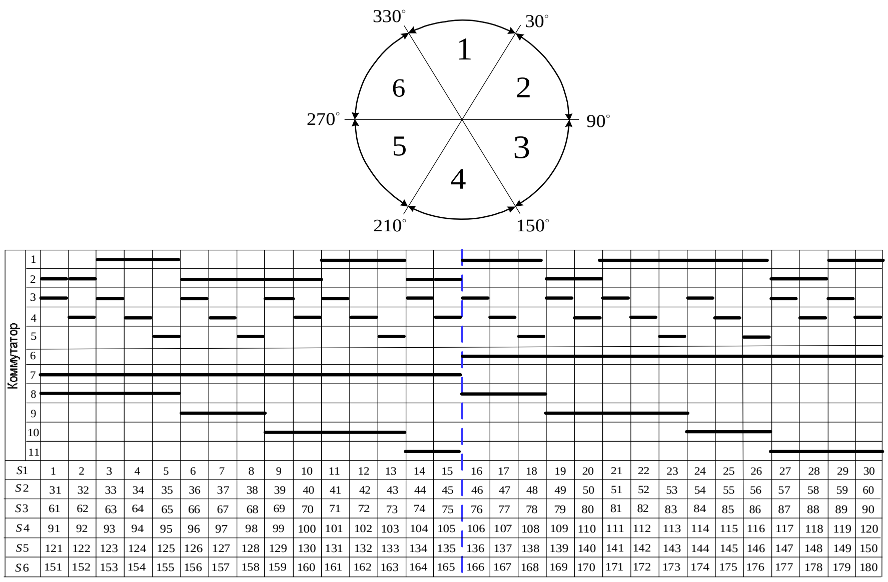

Fig. 11 – Switching diagrams of coarse and fine control.

In addition to the above, as part of the problem an attempt was made of simulation the power exchange between two power systems, one of which belong to the standard of 60 Hz, and the other - to the standard of 50 Hz. The layout diagram of power equipment in the simulation is shown in Fig. 12.

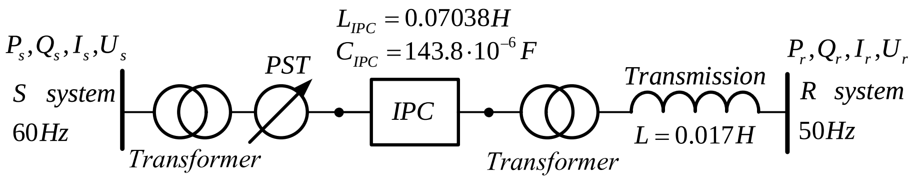

Fig. 12 – The diagram of arrangement of the equipment under simulation.

The simulation procedure of power exchange has been conditionally divided in two stages - static and dynamic.

During the static simulation, at the equality of frequencies (50 Hz) in sending and receiving systems, it was carried out stepwise adjustment of the phase shift at the output PST. Herewith recorded (specified in Fig. 12) indicators of power transmission mode at the sending and receiving systems. Summarized results of the static simulation in the form of relevant graphs (P_r and Q_r) are shown in Fig. 13.

During the dynamic simulation it was carried out the sequence of control operations to ensure of interaction between the blocks of coarse and fine adjustment on condition that the sending system operates with frequency of 60 Hz and the receiving one - with frequency of 50 Hz. Summarized results of the dynamic simulation in the form of corresponding graphs (P_r and Q_r) are shown in Fig. 14 a, b, c, d.

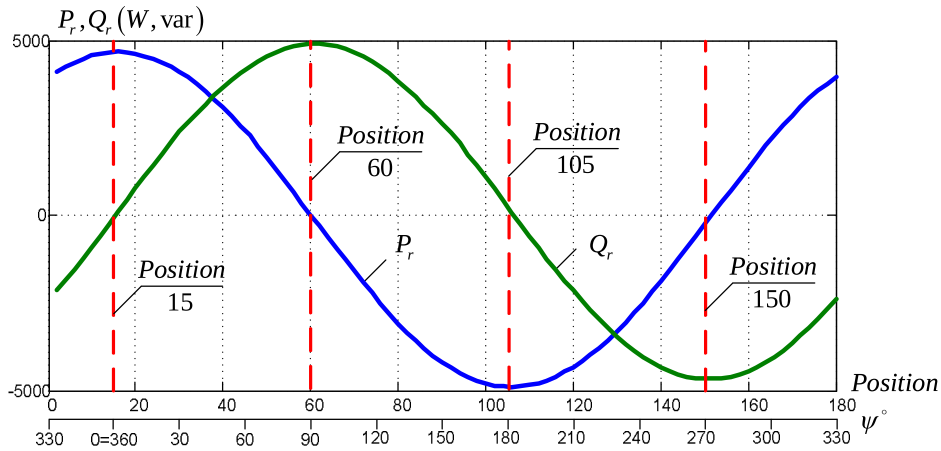

Fig. 13 – The active P_r and reactive Q_r powers at the receiving system as a result of regulation of angle Ψ.

From a consideration of the characteristics shown in Fig. 13 follows that a profound change of the phase shift of voltage at the sending system that equipped with IPC is accompanied by a corresponding change in the magnitude and direction of both active P_r and reactive Q_r power at the receiving system. The specified technical effect is not yet attracted the attention of specialists but may be quite promising in practical terms.

The possibility of practical applications of the observed effect can be illustrated with the use of following typical situations:

1. The maximum positive value of active power P_r corresponding to the position 15 at phase angle Ψ = 0º. Thus, the reactive power at the input of receiving system R is equal to zero. The frequency conversion dynamic characteristics of P_r and Q_r are shown in Fig. 14 a.

2. The zero value of active power P_r corresponding to the position 60 at phase angle Ψ = 90º. Wherein, the reactive power on input of receiving system R takes the maximum positive value (capacitive character). The frequency conversion dynamic characteristics of P_r and Q_r are shown in Fig. 14 b.

3. The maximum negative value of active power P_r corresponding to the position 105 at phase angle Ψ = 180º (reverse). Wherein, the reactive power on input of receiving system R is equal to zero. The frequency conversion dynamic characteristics of P_r and Q_r are shown in Fig. 14 c.

4. The zero value of active power P_r corresponding to the position 150 at phase angle Ψ = 270º. Wherein, the reactive power on input of receiving system R takes the maximum negative value (inductive character). The frequency conversion dynamic characteristics of P_r and Q_r are shown in Fig. 14 d.

These indicated points are used as reference for modeling the dynamic operation modes of cycle converter in the process of power exchange between the asynchronously power systems.

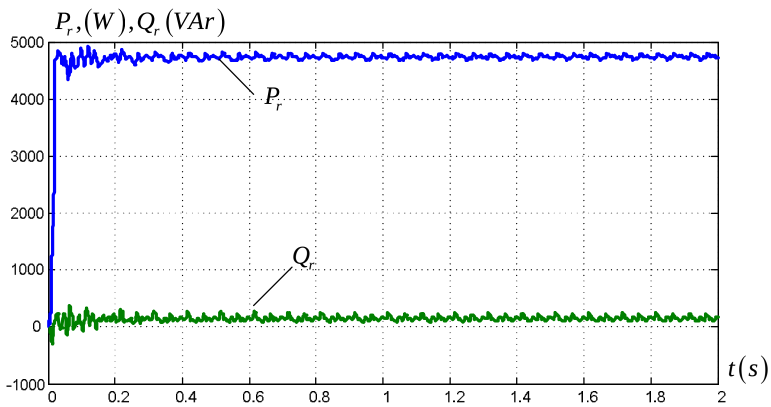

Fig. 14 a – The power characteristics when starting the calculation from position 15.

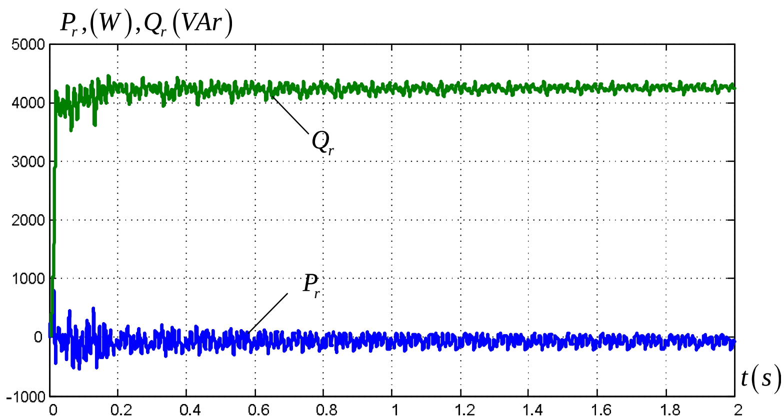

Fig. 14 b – The power characteristics when starting the calculation from position 60.

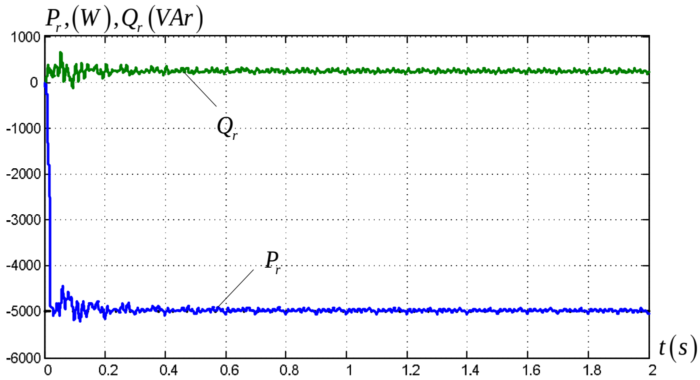

Fig. 14 c – The power characteristics when starting the calculation from position 105.

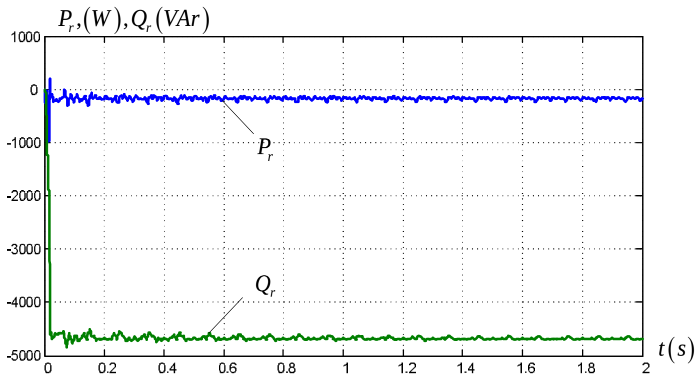

Fig. 14 d – The power characteristics when starting the calculation from position 150.

In this way, the proposed device can be considered as FACTS controller that combines the ability of control the active and reactive power at simultaneously frequencies adaption of asynchronously to both operating power systems. The characteristics, illustrating the shape of operating currents on the buses of system *R* in the process of frequency conversion for the selected positions are presented respectively in Fig. 15 a, b, c, d.

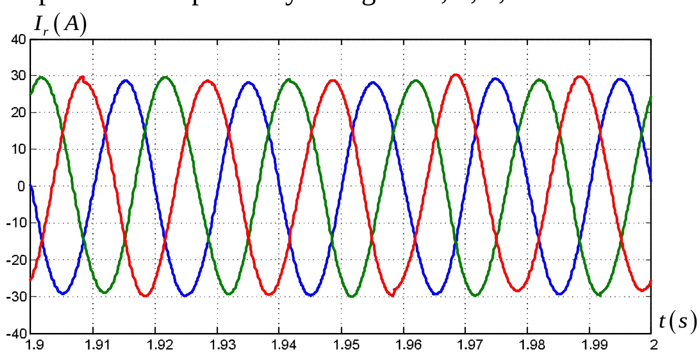

Fig. 15 a – The waveform of output currents when starting the calculation from position 15 (THD = 0.98%).

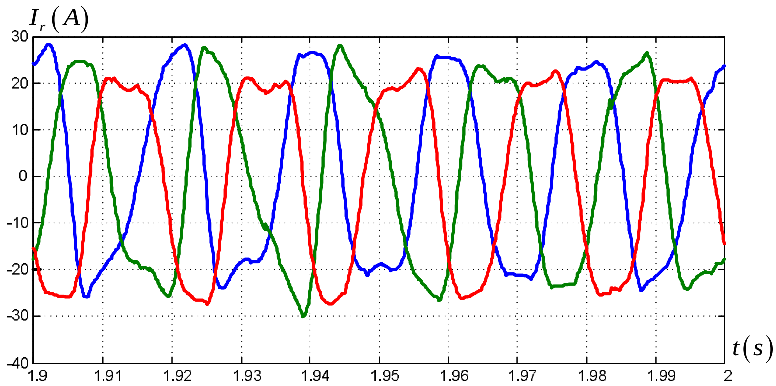

Fig. 15 b – The waveform of output currents when starting the calculation from position 60 (THD = 20.4%).

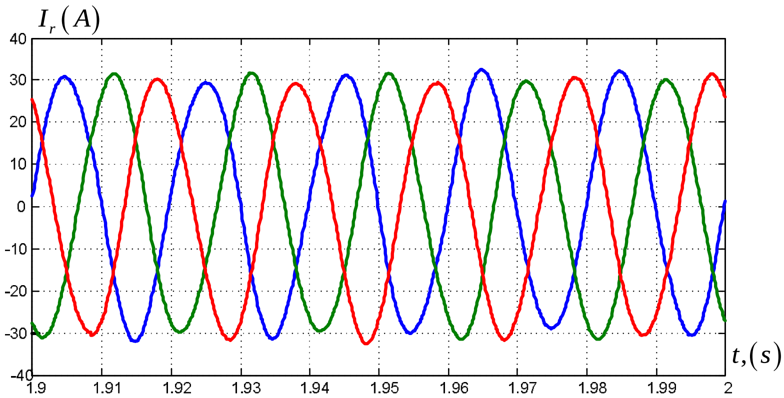

Fig. 15 c – The waveform of output currents when starting the calculation from position 105 (THD = 1.5%).

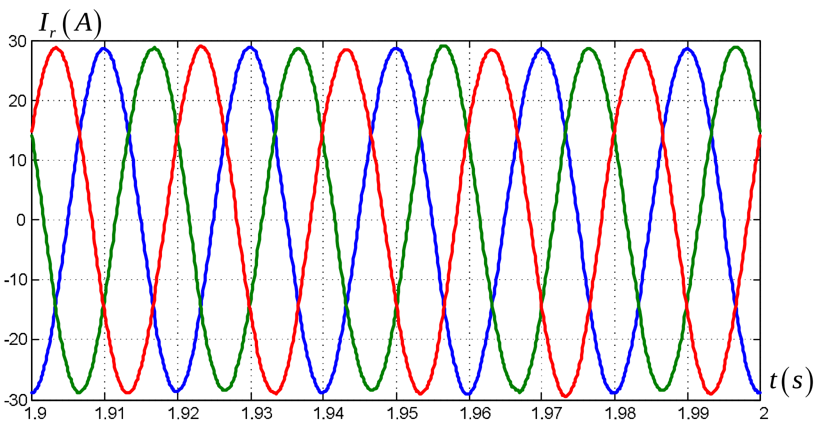

Fig. 15 d – The waveform of output currents when starting the calculation from position 150 (THD = 1.1%).

From an examination of indicated information one can see that for the modes, defined by initial positions №15, №105 and №150 the distortions of sine form of currents are quite insignificant and characterized, respectively, by the following values of harmonic distortion factor (THD): 0.98%, 1.5%, 1.1%.

Wherein, the exception represents a situation defined by starting position 60, in which take place significant distortions of load currents THD = 20.4%. This situation should be considered quite dangerous due to the possibility of resonance phenomena in the receiving system. In cases where there is a need of practical realization of this situation it is required special consideration and justification.

6. Conclusions

1. The fundamental possibility of power exchange between the asynchronously operating electric systems on the base of use of phase-shifting transformer in conjunction with the IPC (Interphase Power Controller) device is shown.

2. A version of a direct converter with high level of precision of phase-shifting angle control, which can be seen as an alternative to Back-to-Back system is proposed.

3. An algorithm of controlling the process of frequency conversion using the blocks for coarse control and fine tuning has been developed.

4. The operational characteristics of frequency conversion are demonstrated.

5. The proposed technology can be considered as a new type of FACTS-controller which provides the adjusting of asynchronously power systems by frequency, the control of active and reactive power magnitude and direction.

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MODELAREA REGIMURILOR CONVERTORULUI DE FRECVENȚĂ REALIZAT ÎN BAZA TRANSFORMATOARELE DE REGLARE A DECALAJULUI DE FAZĂ

(Rezumat)

Problema privind schimbul mutual de energie între două sisteme energetice ce funcționează asincron devine tot mai relevantă odată cu majorarea energiei electrice de la sursele de energie regenerabile. Echipamentele bine cunoscute utilizate în acest scop şi utilizate pe larg sunt Transmisiile de Curent Continuu la Tensiuni Înalte (TCCTÎ) şi Transformatoarele de Frecvență Variabilă (TFV). Ca o alternativă a acestora poate servi instalația ce utilizează principiul transformatoarelor de reglare a decalajului de fază (TRDF). Lucrarea analizează o variantă a astfel de instalație ce funcționează în comun cu instalațiile de tipul IPC (Interphase Power Controller). În lucrarea dată se prezintă descrierea diagramei schematice a acestei instalații, este formulată strategia de control a conversiei frecvenței şi de asemenea prezintă unele caracteristici ce demonstrează procedura de conversie.