CHARACTERISTICS OF TWO CHANNEL STATIC FREQUENCY CONVERTER

CARACTERISTICILE CONVERTORULUI DE FRECVENȚĂ STATIC CU DOUĂ CANALE

Lev CALININ[1], Dmitrii ZAITEV[1], Mihai TIRSU[1], Irina GOLUB[1], Danila KALOSHIN[1]

Abstract: *The object of research is a static transformer frequency converter based on PSF (phase-shifting transformer) with a circular rotation of the output voltage phase relative to the input, made according to the "zigzag-triangle" scheme and controlled by power keys, which can be used to combine parallel-operating power systems having different operating frequencies or standards for maintaining frequency. The aim of the work was to study operational characteristics and evaluate various strategies and laws for controlling the device in order to improve the quality of power transmission via electrical interconnection lines, containing a frequency converter based on the results of computational experiments obtained during structural-simulation modeling. The research results help to determine the feasibility and technical efficiency of the use of new types of converters for combining asynchronously operating power systems.*

Keywords: intersystem communication, static frequency converter, phase-shifting transformer, active power deviation, current non-linear distortion coefficient

Rezumat*: Lucrarea are ca obiectiv cercetarea convertorului static de frecvență de tip transformator, bazat pe TRDF (transformator de reglare a decalajului de fază) cu rotație circulară a fazei tensiunii de ieșire relativ celei de intrare, realizată conform schemei "triunghi zig-zag" și controlată în baza cheilor electronice de putere, care poate fi utilizat pentru a interconecta două sisteme electroenergetice ce au frecvențe de operare sau standarde diferite pentru menținerea frecvenței. În lucrare s-a realizat studierea caracteristicilor operaționale și au fost evaluate diverse strategii și legi pentru controlul dispozitivului în vederea îmbunătățirii calității transmisiei de energie prin linii de interconectare electrică, dotate cu convertor de frecvență bazat pe rezultatele experimentelor de calcul obținute în rezultatul simulărilor. Rezultatele cercetării ajută la determinarea fezabilității și eficienței tehnice a utilizării de noi tipuri de convertoare pentru interconectarea sistemelor electroenergetice cu funcționare asincronă.*

Cuvinte cheie: interconexiune sistem, convertor static de frecvență, transformator de reglare a decalajului de fază, coeficient de distorsiune neliniară

[1] Institute of Power engineering, Chisinau, Republic of Moldova, tirsu.mihai@gmail.com

1. Introduction

The recent interest in frequency-controlled electrical communications [1-5] has led to the development of new technical solutions in this area. Traditionally, the HVDC (High Voltage Direct Current) converters [6-14], as well as the VFT (Variable Frequency Transformers) type electromechanical converters [15-18] are used as the main means of matching the frequency of connected systems. Each of these devices has its own advantages and disadvantages.

The main advantage of VFT is that at any given frequency, the operating voltage at its output terminals always maintains a sinusoidal shape. The disadvantages include: the use of rubbing current collector contacts, which reduces the reliability of the installation; the need for additional energy consumption for control associated with the need to maintain a given level of transmitted power by creating the appropriate torque of the servomotor; the presence of rotor mechanical inertia, leading to the appearance of electromechanical transients; the presence of an air gap between the stator and rotor windings, which is accompanied by a significant increase in the no-load current of the device to a value commensurate with the load current. In addition, the use of VFT is accompanied by a significant increase in the longitudinal inductance of the corresponding transmission path and the need for additional compensating devices.

The main advantage of the HVDC converter is its versatility and speed. Moreover, the most significant drawback of this technical solution is that it is based on the principle of double energy conversion (rectification and inversion) on both the transmitting and receiving sides. In this case, there are significant distortions of the sinusoidal form of operating voltages and currents, requiring the use of special filter-compensation devices.

In this work, we propose a variant of the device for implementing the principle of direct frequency conversion based on PSF (Phase Shifting Transformer-PST) [6,7,8] with circular rotation of the phase, not associated with double energy conversion and without the disadvantages inherent in HVDC and VFT. Such a device may be conditionally called an "AC link".

The study objective was to evaluate and analyze the operating characteristics, strategies and control laws of a static two-channel frequency converter, made according to the "zigzag-triangle" scheme and controlled by power keys at various slip frequencies and load power circuits.

The development of alternative, relative to VFT and HVDC, technical means of frequency conversion for electrical systems will increase the degree of controllability of transport and distribution networks, which is a characteristic trend in the current stage of development of the electric power industry.

2. Device Control Feature and Strategy

The circuit of the studied two-channel frequency converter is presented in Figure 1. Each channel of the static frequency converter consists of multi-winding single-phase transformer groups SN and SM on the transmitting side and RN and RM on the receiving side, the primary windings of which are connected in a zigzag circuit. Such a connection is used to suppress the third harmonic of the current. Unregulated secondary windings of transformer devices are connected according to the "triangle" scheme, to the vertices of which the corresponding control windings are connected, which are a block of "thin" regulation.

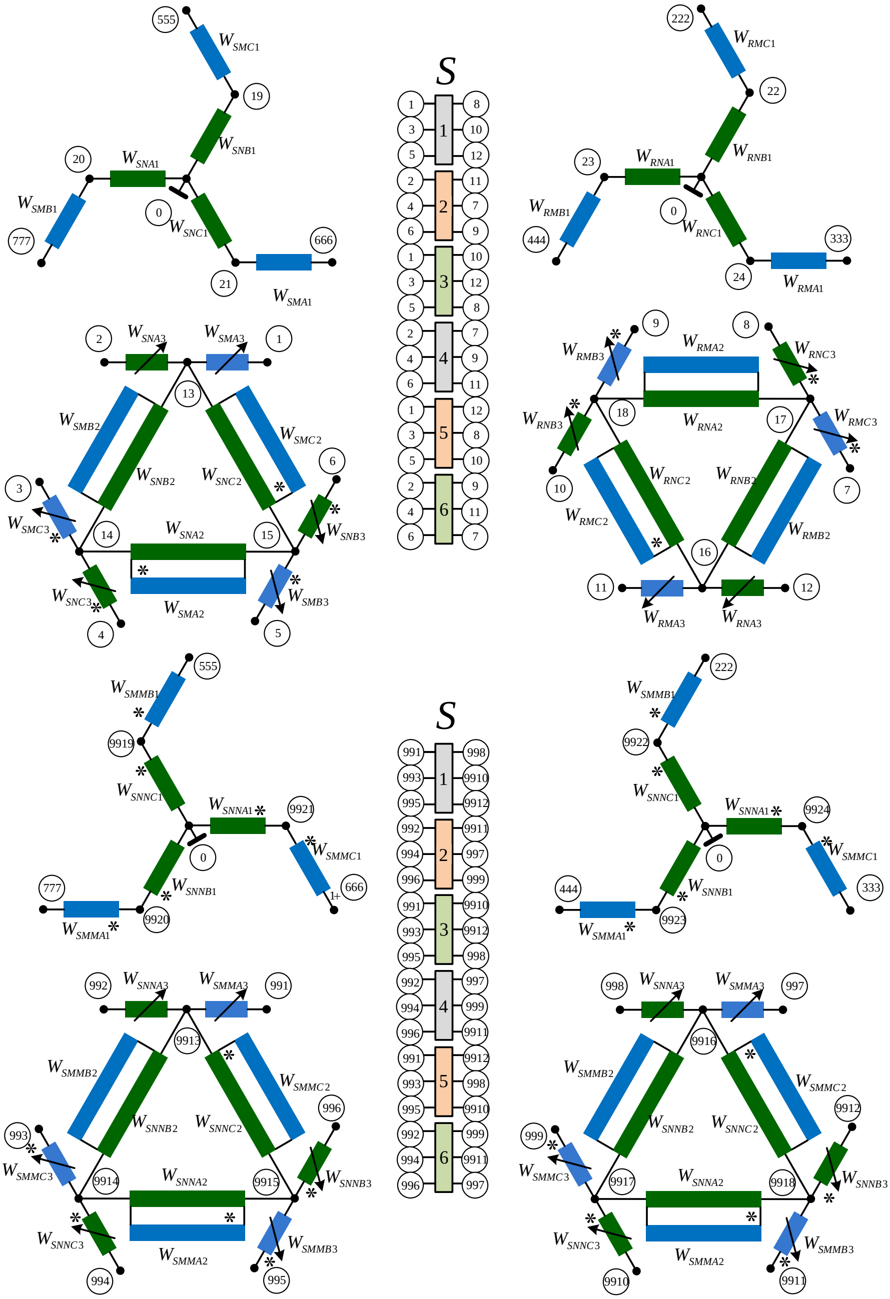

Figure 1. Scheme of a static two-channel frequency converter.

The next notes are used on Figure1:
- common points of scheme are marked with same number in circle;
- (*) – the end of winding;
- windings with arrows – adjustable windings;
- winding designation example: W_{SNA1} - winding 1, Phase A Transformer group N, sending system S.

The control windings of a static frequency converter, designed to control the angle in 60 degree sectors, are a “thin” regulation unit, which consists of appropriately sectioned adjustment windings with a set of power switches, which allow controlling with a given regulation step discreteness. For the study, two options for sectioning the regulation windings and regulation laws are developed.

1. The winding section diagram and the control law that implement the 24-position control strategy with a switching resolution of 5 ° are presented in Figure2,3, respectively. Position number 1 in this case is the starting one. Switching is carried out according to the scheme 1-48-1-48, etc., i.e. cyclically for all keys (Figure 3).

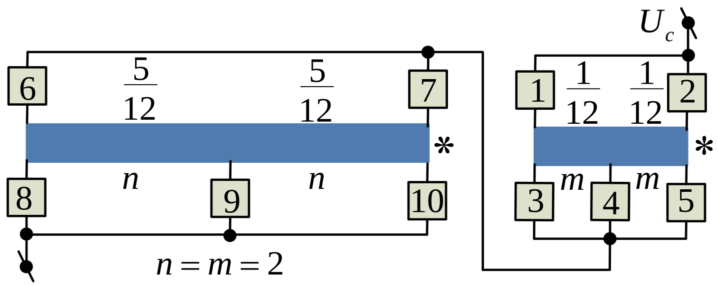

Figure 2. Control winding sectioned under 24 switching positions.

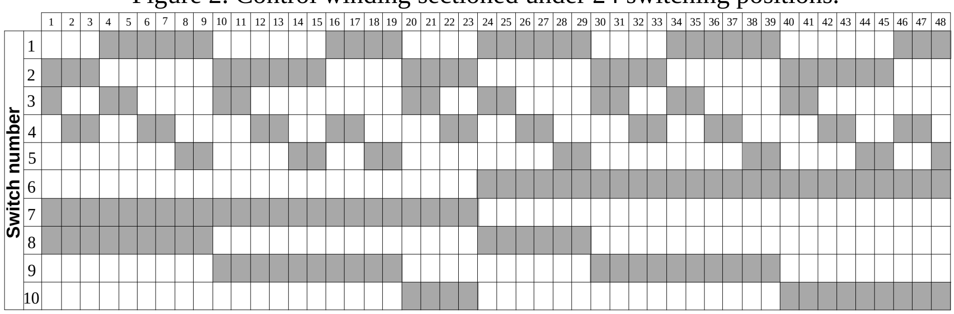

Figure 3. Converter control strategy with step resolution of 5 degrees.

2. The winding sectioning scheme and the control law implementing the 48-position control strategy are presented in Figure 4,5, respectively. In this case, the step is 2.5°. In this case, the starting position is position No. 25. Switching is performed according to the circuit 25-49-1-25-49-1-25, etc., for all keys (Figure5).

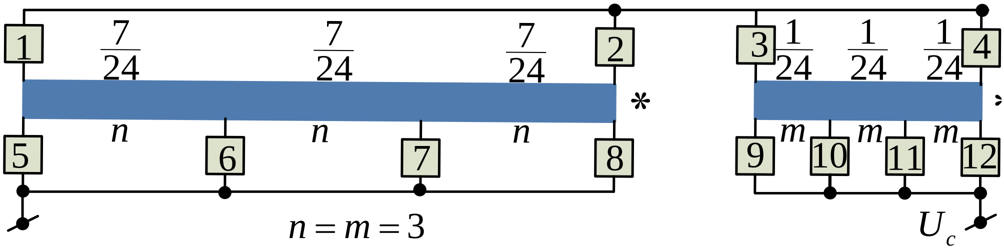

Figure 4. Control winding sectioned under 48 switching positions.

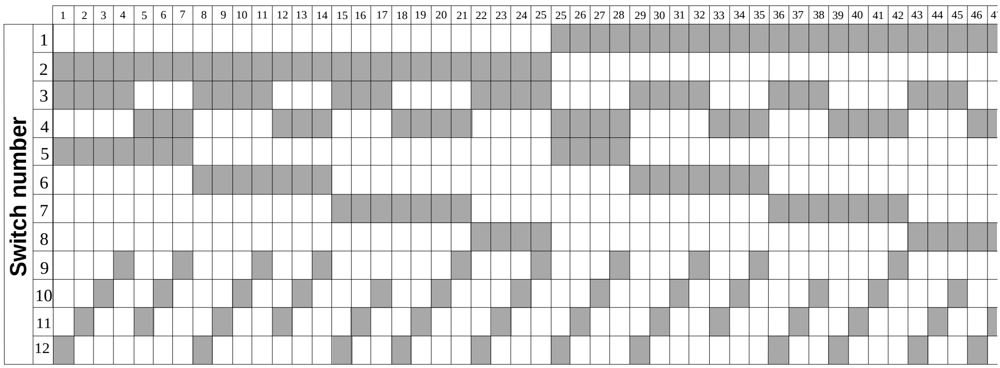

Figure 5. Converter control strategy with step resolution of 2.5 degrees

For the proposed control schemes, the following notations are used:

n - maximum control winding resolution,

m - minimum control winding resolution.

Then the voltage of the control winding:

$$U_c = mU_m + nU_n. \quad (1)$$

Voltage of the minimum section of the control winding:

$$U_m = \frac{U_c}{m + n(1 + 2m)} = \frac{U_c}{p}. \tag{2}$$

Voltage of the maximum section of the control winding:

$$U_n = (1 + 2m)U_m. \tag{3}$$

Total number of control steps:

$$q = 1 + 2\left[m + n(1 + 2m)\right]. \tag{4}$$

Sectioning of the winding and the law of 48 positions switching allowed to reduce the switching step from 5° (when using 24 switching positions) to 2.5° and can improve the quality of conversion. The advantage of the developed power key compared to the traditional one is that during regulation, the number of series connected keys in operation always remains equal to 4, regardless of the regulation steps number, which can significantly improve the reliability indicators of the control system.

A set of conditional power electronic switches *S* forms a block of “rough” regulation of the converter. The law of power key controls that implements the strategy of “rough” regulation is presented in Figure6. The starting position of the “rough” control keys for each channel is shifted relative to each other by an angle of 30°.

		1 канал												2 канал										
$S1$	№$_p$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
$S2$	№$_p$	48	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26
$S3$	№$_p$	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
$S4$	№$_p$	96	95	94	93	92	91	90	89	88	87	86	85	84	83	82	81	80	79	78	77	76	75	74
$S5$	№$_p$	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119
$S6$	№$_p$	144	143	142	141	140	139	138	137	136	135	134	133	132	131	130	129	128	127	126	125	124	123	122

Figure 6. The law of power keys control of “rough” regulation.

A two-channel frequency converter made on the basis of the “zigzag” scheme allows to halve the number of “rough” control keys (switchings), which switch not through 60° as in the devices studied by the authors of the work earlier [19-23], but after 120°.

3. Modeling conditions and results

Computational experiments were carried out on the basis of proven structural and simulation SPS-models of the device made in the Matlab environment. The operational parameters of the static converter windings are taken into account the possibility of building a laboratory sample in the future:

$$
\begin{aligned}
&U_{SM1} = U_{SN1} = U_{RM1} = U_{RN1} = 133V;\\
&I_{SM1} = I_{SN1} = I_{RM1} = I_{RN1} = 24A;\\
&U_{SM2} = U_{SN2} = U_{RM2} = U_{RN2} = 345V;\\
&I_{SM2} = I_{SN2} = I_{RM2} = I_{RN2} = 7A;\\
&U_{SM3} = U_{SN3} = U_{RM3} = U_{RN3} = 345V;\\
&I_{SM3} = I_{SN3} = I_{RM3} = I_{RN3} = 7A;\\
&U_{SM4} = U_{SN4} = U_{RM4} = U_{RN4} = 57,5V;\\
&I_{SM4} = I_{SN4} = I_{RM4} = I_{RN4} = 12A;\\
&U_{SM5} = U_{SN5} = U_{RM5} = U_{RN5} = 57,5V;\\
&I_{SM5} = I_{SN5} = I_{RM5} = I_{RN5} = 12A.
\end{aligned}
\tag{5}
$$

When modeling, the following conditions were met:

- active load was supplied in accordance with the schemes Figure7,8.

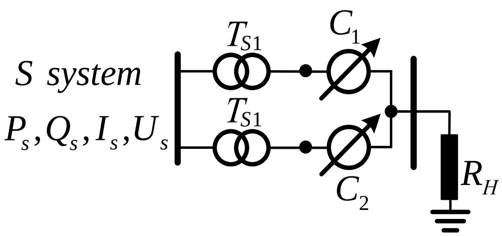

Figure 7. The scheme of the experiment when operating a 2-channel converter for active load.

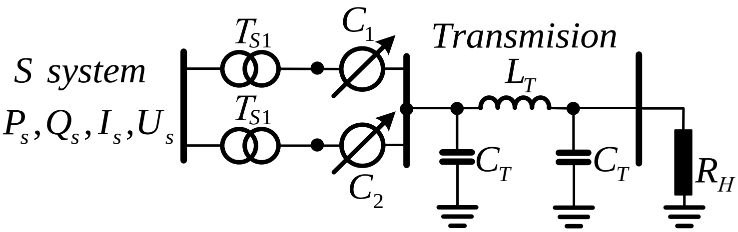

Figure 8. The scheme of the experiment during the operation of a 2-channel converter for active load through power lines 30°.

- simulation time $t = 2$ s;
- номинальное voltage of transmitting and receiving systems $U_s = U_r = 230V$;
- angle of the transmission system $\delta_s = 0°$;
- установленная мощность устройства составляет $19152VA$
- the value of the transmitted active power was $P_r = 5700W \pm 5\%$;
- the output current of the device for all the calculation experiments was maintained at $I_r = 24A \pm 5\%$, which corresponds to the nominal value and load resistance $R_H = 9Ohm$;
- frequency ratios of transmitting and receiving systems are adopted as follows: 60/50Hz, 50/60 Hz, 50/49Hz, 50/49,6 Hz.

To assess the quality of frequency conversion and power transmission, the following operational parameters were used:

- degree of stability (deviation) of the transmitted active power on the transmission system $(\partial P_s, \%)$ and the load $(\partial P_r, \%)$;
- harmonic distortion current on the transmitting system $(THD(I_s), \%)$ amd the load $(THD(I_r), \%)$.

Based on the results of computational experiments for comparative analysis, Figure9-12 shows histograms of operating parameters at various slip frequencies and various discreteness of “fine control”. The operating parameters with the “L” index are given for the load supply option according to the Figure 8 scheme, without the index - Figure 7.

The figures marked with letters show:

a - is the stability degree of the transmitted active power,

b - coefficient of nonlinear current distortion

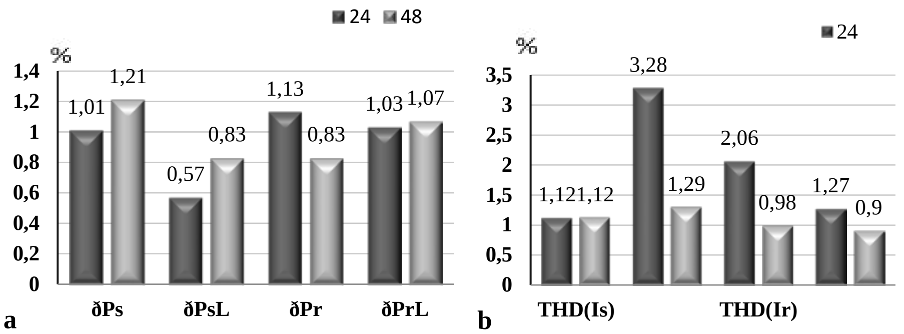

Figure 9. Diagrams of operational parameters when converting 60Hz to 50Hz

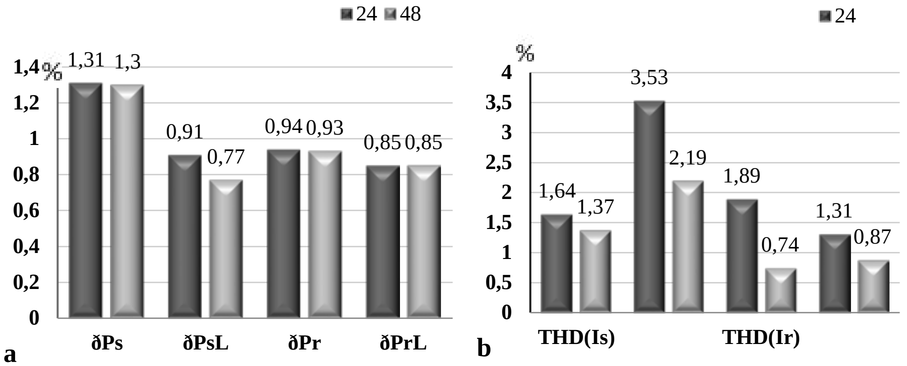

Figure 10. Diagrams of operational parameters during 50Hz to 60Hz conversion

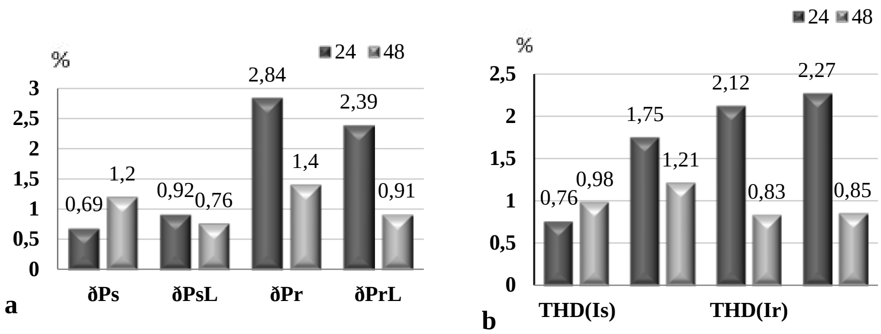

Figure 11. Diagrams of operational parameters when converting 50Hz to 49Hz

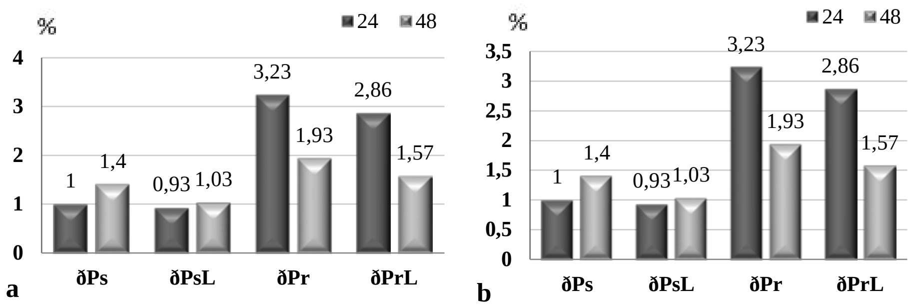

Figure 12. Charts of operational parameters when converting 50Hz to 49.6Hz

Analyzing the results of computational experiments, we can come to the following conclusions:

- When working on a load, the magnitude of the power fluctuations at the receiving system with a 48-position switching law is higher than with a 24-position one with various types of frequency conversion. Moreover, the difference is greater, the lower the slip frequency. The same nature of the power fluctuation is observed when working on an active load through power lines with the only difference being that the absolute value of the deviation from the average decreases by about 30-40%.

- On the receiving system, the use of 48-position control looks more efficient than 24-position control. The maximum effect is observed at a slip frequency of 0.4 and 1 Hz. However, it should be noted that in this case the deviation is significantly lower than when converting to 10 Hz. At a slip frequency of 10 Hz, the magnitude of the power fluctuation is close in value both when supplying the load through power lines, and without it.

- In general, at different slip frequencies between the transmitting and receiving systems, the degree of oscillation for the transmitting system is in the range of 0.69 ÷ 1.4% (when working through power lines - 0.57 ÷ 1.03%), for the receiving system in the range of 0, 83 ÷ 3.23% (when working through power lines - 0.85 ÷ 2.86%). This ensures a sufficiently high level of stability of the transmitted power during the frequency conversion.

When analyzing the currents $THD(I_s)$ on the transmitting system, we can conclude that the options for the 24th and 48th positional regulation are approximately equal. It is seen that the smallest value of the coefficient of nonlinear distortion occurs in the case of a slip frequency of 0.4 and 1 Hz. The maximum value is obtained when transmitting power from low frequency to high (50 / 60Hz).

Connecting the load through the power transmission line leads to a significant (more than two-fold) increase in the non-linear distortion coefficients of the currents on the transmission system for the option of 24-position regulation, but at 48 positions there is no significant increase. It should be noted that when supplying a load through a power transmission line, conversion at 48 control positions provides a significant reduction in THD compared to 24 position control for all conversion modes. THD reduction range can reach 0.5 ÷ 2.0%

For the receiving system, the conversion at 48 switching positions in all modes of load connection and frequency combinations is much more efficient than 24-position regulation. The decrease in the THD current distortion coefficient can reach 1.0 ÷ 1.3%.

The maximum THD reduction effect for 48-position control is observed at the load at a slip frequency of 0.4 and 1 Hz.

4. Conclusions

As a result of the work done, we can draw the following conclusions:

1. A schematic version of a two-channel frequency converter based on a phase-rotation transformer with circular rotation of the output voltage phase made according to the "zigzag-triangle" scheme is proposed;

2. Sectionalized control windings and control strategies have been developed that provide 48 switching positions in each 120° sector of the “rough” regulation with discreteness 2,5°, and a control strategy that provides 24 switching positions in each 120° sector of the “rough” regulation with discreteness 5°.

3. Structural-simulation models of two-channel converters with 48 and 24 switching positions were constructed and debugged, based on which calculation experiments were carried out. The results of the experiments illustrated the feasibility of the idea of constructing a frequency converter based on the proposed device circuit.

5. The conversion quality was evaluated at various slip frequencies between the transmitting and receiving systems with various device connection schemes. It is shown that the conversion quality parameters significantly differ for 48 and 24 switching steps at different slip frequencies between the transmitting and receiving systems. In general, an analysis of the parameters characterizing the quality of the conversion allows us to conclude that the 48-position control law is effective.

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