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Multi-pulse rectifier as a means of electromagnetic compatibility improvement in three-phase networks with sliding delta winding transformer

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Abstract The article is devoted to the principle of creating a technical means to improve the electromagnetic compatibility of three-phase rectifiers in AC supply networks. The principle of constructing the circuit solution of this technical device is described and the calculated expressions for its implementation are presented on the basis of transformer converters of the number of phases and the connection of their windings into a “sliding delta”. This solution allows implementing a controlled mode of increased equivalent pulsation of rectification and providing high-energy performance in the supply network by regulating the phase shifts of three-phase voltages supplying three-phase rectifiers, which is confirmed by a series of model experiments.

1. Introduction

In recent years, there has been an increase in the number of rectifying devices operating in the links of a three-phase AC power supply system.

It should be noted that any rectifier in the AC network acts as a non-linear load, which produces a non-sinusoidal current and leads to the appearance of high harmonics [1]. This, in turn, causes a distortion in the shape of the supply voltage curve, which negatively affects adjacent AC consumers, which ultimately have to be powered with non-sinusoidal voltage [2-3].

So, conventional rectifiers negatively affect the three-phase AC network. Among non-linear loads, the most common are valve converters and various control devices, which are powered at 380/220 V.

However, when the number of non-linear devices increases, it is necessary to minimize the harmonics of current and voltage in 380/220V networks. Nowadays the number of non-linear consumers is huge and it tends to be growing. Such tendency is characteristic of any type of power supply system: industrial, urban, rural etc. For this reason the specialists involved in designing power supply systems of different types show more and more interest in current non-sinusoidality caused by low non-linear loads and the methods to control them [4].

2. The methods to control high harmonics

It is known that if the number of pulsations of a three-phase rectifier is increased with any technical way this will reduce the degree of its negative impact on the AC network. Thus, an increase in the pulsation of a rectifier operating in a three-phase network approximates the shape of its mains current curves to a sine wave and reduces the level of high harmonics.



The theory that explains the formation of network currents of multi-pulse rectifiers has been known for a long time, so there is the formula [5]:

$$I_k = k \cdot m \pm 1, \quad \text{at } k \in N \quad (1)$$

that determines the ordinal numbers of the expected (canonical) harmonics in the mains current curve consumed by a multi-pulse rectifier with the number of ripples m . What is more, the greater the ordinal number of the harmonic current consumed by the m -pulse rectifier from the three-phase network, the smaller the magnitude of this harmonic. It is known that in relative units:

$$|I_k^*| = \frac{1}{k}. \quad (2)$$

It follows, for example, that the 6-pulse rectifier in the three-phase AC network will produce high harmonics: the fifth one with a level of 20%, the seventh with a level of 14%, the eleventh with a level of 9%, the thirteenth with a level of 7.6%, etc. At the same time in the harmonic of the 12-pulse rectifier of the same capacity from the listed above, will contain only the 11th and 13th harmonics with the same levels [6].

The method of providing electromagnetic compatibility of the rectifier in the AC network by increasing its pulse rate is effective and well known per se. However, it is impossible to increase the pulsation of a huge fleet of already existing rectifiers used in three-phase AC networks. Most of them employ 6-pulse rectifiers straightening over a period [7].

It is proposed to implement in the three-phase AC power supply system such joint operation modes of 6-pulse rectifiers (because they are the majority) which by the resulting effect on the supply network will be equivalent to the operation of 12-pulse rectifiers.

Thus, the degree of negative influence of rectifiers with an insufficiently high number of pulsations during the period (6-pulse rectifiers) will be reduced and, in the end, a partial improvement in the shape of the voltage curve of the three-phase supply network is achieved. To ensure a such mode of 6-pulse rectifiers joint operation in the power supply system, which would be equivalent to 12-pulse rectifiers operation, it is necessary [8] to allocate two systems of three-phase voltages with a 30° phase shift (from the available in the three-phase network) and to feed 6-pulse rectifiers with them.

Each of the selected three-phase voltage systems should share the rectifier load evenly, feeding its part of 6-pulse rectifiers. So, in the power supply system, the equivalent 12-pulse rectification mode will be achieved by the aggregation method.

However, in practice, 6-pulse rectifiers are powered with step-up transformers connected in various schemes (combination of transformer winding connection groups: a “delta-star”, a “delta-delta”).

As a result, the total load is not only stochastically variable in nature of the impact on the power supply system, but also composed of different groups of connections of transformers windings supplying 6-pulse rectifiers. Therefore, for the new connection of the 6-pulse rectifier load, it is impossible to specify in advance which equivalent phase shift of the supply voltage system would be required to get the equivalent 12-pulse rectification mode as a result of the joint operation of the attached load and the load of the rectifiers already available in the system.

In this work it is proposed to equip the new three-phase AC rectifiers with an adaptive phase-shifting regulator. The concept of such regulation is based on the analysis of the shape of the voltage curve of the three-phase supply network and the choice of such a phase shift of the voltage system feeding this rectifier, which would lead to an increase in the equivalent pulsation mode produced by rectifiers joint operation in the power supply system.

It is obvious that since most three-phase rectifiers provide 6-pulse mode of rectification, to achieve 12-pulse mode, it is necessary to have a phase shifting regulator with a range of phase changes from 0° to $\frac{2\pi}{m} = \frac{360^\circ}{12} = 30^\circ$.

The analysis of the voltage curve of the three-phase supply network and the development of the control action to select the phase shift of the supply voltage system should be assigned to the

microprocessor system. The technical solution that implements both phase shift and transformation of the supply voltage levels is rational to base on phase-shifting transformer converters. (PhSTC) [6].

3. The choice of phase-shifting transformer converters (PhSTC) must be reasonable

The most convincing selection criterion is to minimize the cost of equipment and the typical capacity of transformers. Phase-shifting transformers [9] which could smoothly shift (rotate) the phases of secondary voltage systems do not satisfy this criterion, and they have the movable parts increasing the total cost of these transformers. Among the simple, having no moving parts and therefore the cheapest ones, are PhSTC based on three-phase transformers with a flat magnetic system. The windings of these transformers are usually connected in the circuits known as “star”, “delta” (“triangle”) and “zigzag”.

It is known that the typical capacity of PhSTC windings, connected in a “star” or a “delta”, in relative units is 1.0. However, for “zigzag” winding connection, this capacity is higher than 1.0 and depends on the phase shift, which this connection diagram forms during the operation.

Based on the theory presented briefly, it is obtained that for the PhSTC “zigzag” scheme, the dependence of a typical capacity will vary from 1.0 to 1.15 (Figure 1).

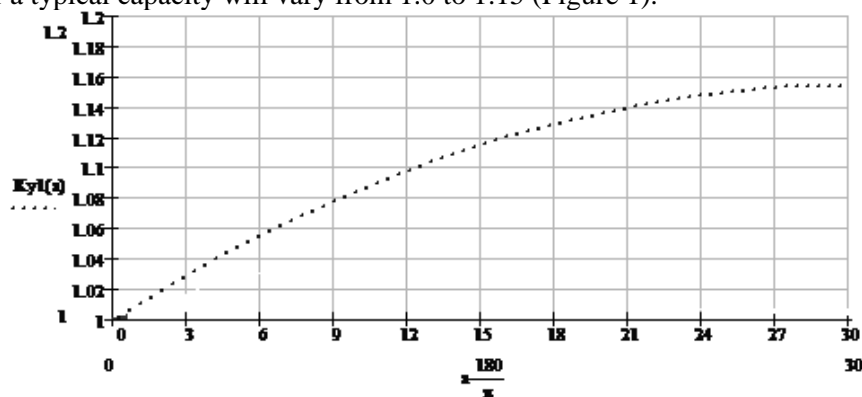


Figure 1. K_T – angle magnitude dependence characterizing the shift of the resulting voltage vectors.

It should be recognized that the excess of PhSTC typical capacity by 15% is already a lot.

The principle of achieving significantly lower values of typical capacity of PhSTC windings is well known [11,12]. It is based on a combination of the advantages of winding connections into closed circuits (“delta”) and open circuits (“star”). The so-called “sliding delta” [11,12] is obtained on its basis. The possible scheme is given in Figure 2.

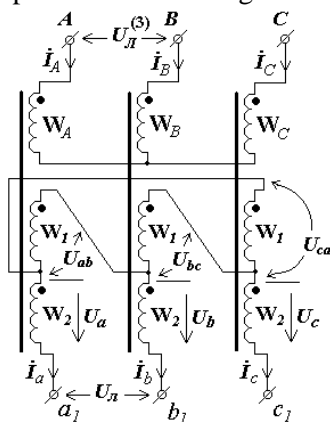


Figure 2. The scheme of phase-shifting transformer or PhST with sliding delta windings connection.

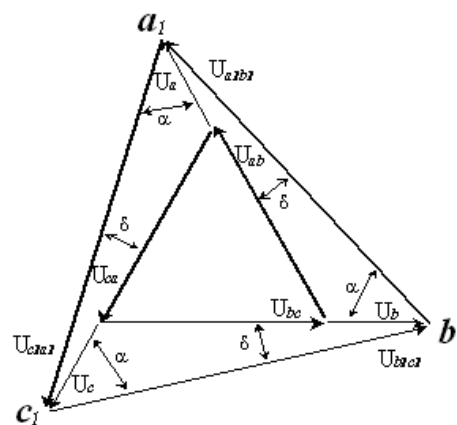


Figure 3. Voltage vector diagrams of the PhSTC secondary windings for sliding delta.

A vector diagram in Figure 3 explains how it works. Using vector diagrams, it is easy to obtain a connection between the linear voltage of the sliding delta U and the phase voltages U and U of W1 and W2 windings, respectively:

$$\begin{aligned} U_i &= 2U_\delta \sin(\pi/6 - \sigma_i); \\ \dot{U}_{\Delta i} &= 2\sqrt{3}U_\delta \sin(\sigma_i). \end{aligned} \quad (3)$$

In accordance with the ratio at $\sigma_i = 0$, the voltage of the windings will be $\Delta \dot{U} = \dot{U}_\phi$, $\dot{U}_\Delta = 0$ which corresponds to the star winding connection diagram of the converter, and at $\sigma_i = \pi/6$ – to “delta” as $\Delta \dot{U} = 0$ and $\dot{U}_\Delta = \dot{U}_{JL}$.

Typical capacities of primary or secondary windings connected in such scheme are:

$$S_\Sigma = S_{\Sigma\Delta} + S_{\Sigma Y} \quad (4)$$

including rated capacity values of a polygon $S_{\Sigma\Delta}$ and a multi-ray star $S_{\Sigma Y}$.

In this case, the power supplied to the m-phase scheme of the “sliding delta”, or withdrawn from it, will look as follows:

$$S_{\Sigma H} = m \cdot U_\phi \cdot I_\phi = \frac{m}{2 \sin \frac{\pi}{m}} U_{JL} \cdot I_{JL} \quad (5)$$

Taking the above into account, the “sliding delta” typical capacity in relative units can be estimated with the following ratio

$$K_Y = \frac{S_\Sigma^*}{S_{\Sigma H}^*} = \frac{(U_\Delta^* + 2U_Y^* \sin \frac{\pi}{m}) I_{JL}^*}{U_{JL}^* I_{JL}^*}, \quad (6)$$

where U_ε^* is linear voltage of the “sliding delta” scheme in relative units:

$$U_{JL}^* = \sqrt{(U_\Delta^*)^2 + 4U_Y^* (U_\Delta^* + U_Y^*) \sin^2 \left(\frac{\pi}{m} \right)}, \quad (7)$$

As

then K value of a “sliding delta” scheme will be found with the following ratio, assuming $m=3$:

$$K_Y = \frac{U_\Delta^* + \sqrt{3}U_Y^*}{\sqrt{3(U_Y^*)^2 + 3U_\Delta^* \cdot U_Y^* + (U_\Delta^*)^2}}. \quad (8)$$

This can be represented graphically in Figure 4 and to compare the relative values of typical capacity windings PhSTC connected by the schemes of “zigzag” and “sliding delta”.

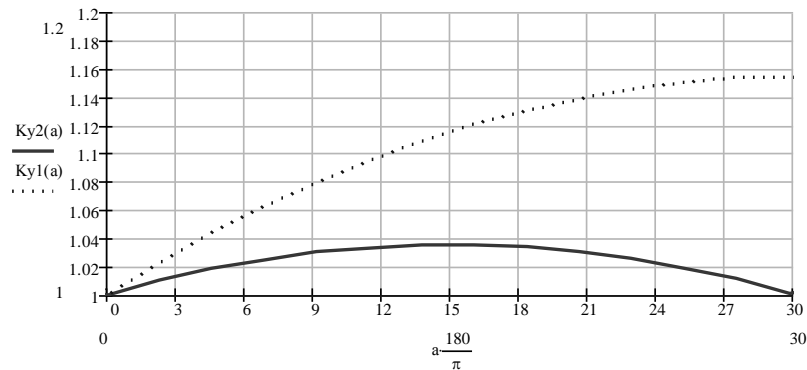


Figure 4. Dependencies of the type $K_Y = f(\delta)$ for PhSTC using “zigzag” and “sliding delta” schemes.

Thus, PhSTC based on a “sliding delta” connection has an essential advantage because the typical capacity of its windings is much lower than that of PhSTC based on “zigzag” connection and doesn't exceed $K_y^{\max} \approx 1.03527$ with a ratio of $\frac{U_D^*}{U_U^*} = \sqrt{3}$, which provides phase shift of the voltage secondary system by 15° .



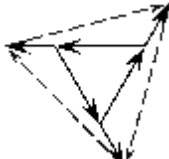
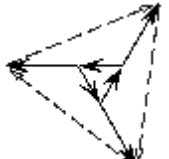
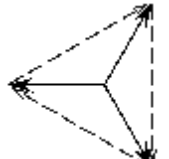
It is necessary to obtain in a general form the universal working formulas that define in relative units the number of turns of the PhSTC windings connected in a sliding delta. And we work out the PhSTC scheme itself, which will allow phase shifts of the system of secondary linear voltages relative to the system of primary voltages, without changing their effective values.

The simplest circuit engineering method of preserving the effective values of the system of secondary line voltages, when phase shifts change, is to simultaneously switchtap the windings W1 and W2. Using the original system (3) and taking into account the expressions (4), we can write the system of equations to determine the number of turns of the windings W_1^* and W_2^* in relative units:

$$\begin{aligned} W_1^* &= 2\sin(\pi/6 - \sigma_i); \\ W_2^* &= 2\sqrt{3}\sin(\sigma_i). \end{aligned} \quad (9)$$

Let PhSTC with sliding delta windings be able to carry out shifts in the range from 0° to 30° with an equal step, for example, $\sigma = 0^\circ, 7.5^\circ, 15^\circ, 22.5^\circ, 30^\circ$ switching intermediate winding taps. In this case, in accordance with the system (9), we obtain the necessary series of the numbers of turns, compiled in the form of table 1.

Table 1. A number of turns W_1^* and W_2^* in PhSTC sliding delta

shift σ	0°	7.5°	15°	22.5°	30°
W_1^*	1.0	0.7653	0.517	0.2610	0
W_2^*	0	0.1507	0.2988	0.4418	0.577
The schemes of vector diagrams of secondary voltage windings					

The schemes of vector diagrams of windings secondary voltages in Table 1 showed that during phase shifts σ due to the simultaneous change in the number of turns W_1^* and W_2^* (switching of the corresponding taps), the linear voltage module was maintained (dotted arrow).

Thus, both the windings W1 forming the sides of a triangle and the windings W2, forming the rays of a star, should have a series of taps. In this example, these taps divide the winding into 4 sections. To determine the number of turns for each section, it is necessary to find the corresponding differences between adjacent numbers of turns from table 1.

As a result of the analysis of the above formulas and the results of table 1, we obtain the general formula that defines in relative units the number of turns of intermediate taps for the windings forming a closed connection in a triangle:

$$W_{\Delta i}^* = 2\sin\left(\frac{\pi}{6}\left(1 - \frac{n-i}{n-1}\right)\right) - 2\sin\left(\frac{\pi}{6}\left(1 - \frac{n-i+1}{n-1}\right)\right) \quad (10)$$

and open connections of the star rays:

$$W_{YI}^* = \frac{2}{\sqrt{3}} \sin\left(\frac{\pi}{6} \left(\frac{n-i}{n-1}\right)\right) - \frac{2}{\sqrt{3}} \sin\left(\frac{\pi}{6} \left(\frac{n-i-1}{n-1}\right)\right), \quad (11)$$

where n is the number of steps that determine the phase shift σ and $1 \leq i \leq n$. After trigonometric transformations, the expressions (10) and (11) are simplified. As a result, functioning expressions are obtained to determine the numbers of turns of the intermediate sections that form the sides of a sliding delta to create PhSTC that provides a stepwise shift σ from 0° to 30° :

$$W_{\Delta i}^* = 4 \sin\left(\frac{\pi}{12(n-1)}\right) \cos\left(\frac{\pi(2i-3)}{12(n-1)}\right), \quad (12)$$

and the number of turns of the intermediate sections that form the star rays:

$$W_{Yi}^* = \frac{4}{\sqrt{3}} \sin\left(\frac{\pi}{12(n-1)}\right) \cos\left(\frac{\pi(2n-2i-1)}{12(n-1)}\right). \quad (13)$$

Let us check the working expressions (12) and (13) and build the layout of the taps of the PhSTC windings. So, in this example, $n = 5$.

Therefore, the expressions (12) and (13) allow one to calculate easily:

$$W_{\Delta 1}^* = 0, W_{\Delta 2}^* = 0.26105, W_{\Delta 3}^* = 0.25658, W_{\Delta 4}^* = 0.24773, W_{\Delta 5}^* = 0.23463, W_{Y1}^* = 0.13546, W_{Y2}^* = 0.14303, W_{Y3}^* = 0.14814, W_{Y4}^* = 0.15072, W_{Y5}^* = 0.$$

According to the results obtained, construct the schemes of taps location (Figure 5) and compile summary Table 2.

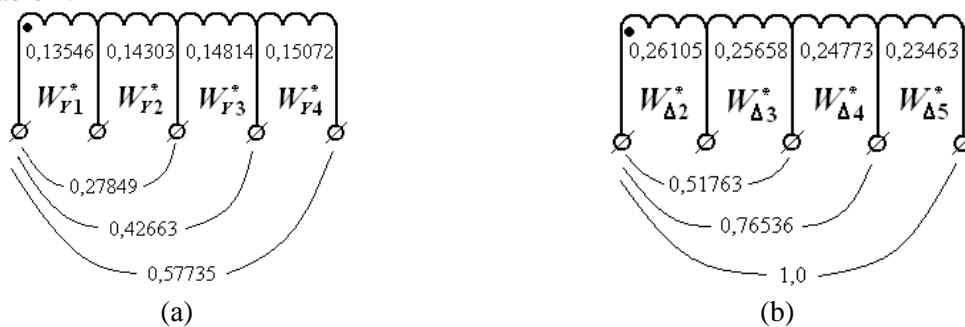


Figure 5. Layout of connected PhSTC windings taps: (a) in “star”, (b) in “delta”.

Table 2. Check table information of the sum of the numbers of windings

Degree i	W_{Yi}^*	Total sum $\sum W_{Yi}^*$	$W_{\Delta i}^*$	Total sum $\sum W_{\Delta i}^*$	Shift σ
1	0.13546	0.13546	0	0	0^0
2	0.14303	0.27849	0.26105	0.26105	7.5^0
3	0.14814	0.42663	0.25658	0.51763	15^0
4	0.15072	0.57735	0.24773	0.76536	22.5^0
5	0	0.57735	0.23463	1.0	30^0
Check sum	$0.57734 \approx \frac{1}{\sqrt{3}}$	0.57735	1.0	1.0	

The construction of the final PhSTC scheme with “sliding delta” windings with a five-step shift σ . The “sliding delta” winding connection scheme can be constructed both on the secondary side of PhST transformers, similar to Figure 2, and on its primary side. Taking into account the fact that a

multi-pulse adaptive rectifier developed on this basis should be universal, it is more expedient to build a switching system for the windings on the primary side. This will allow simultaneously with the switching of the windings to shift not only the vector of the resulting voltage, but also the working magnetic field in the rods of the transformer feeding the multi-pulse rectifier.

Such circuit principle of shift control σ will be convenient if it is necessary to further increase a pulsation number, using the aggregation method, since the secondary windings of the PhSTC in this case do not participate in switching and can be connected in “star”, “delta”, etc.

So, for a six-pulse adaptive rectifier based on PhSTC groups with a five-stage phase shift, a diagram of the primary windings connections and the places of the switch taps connection is obtained and shown in Figure 6.

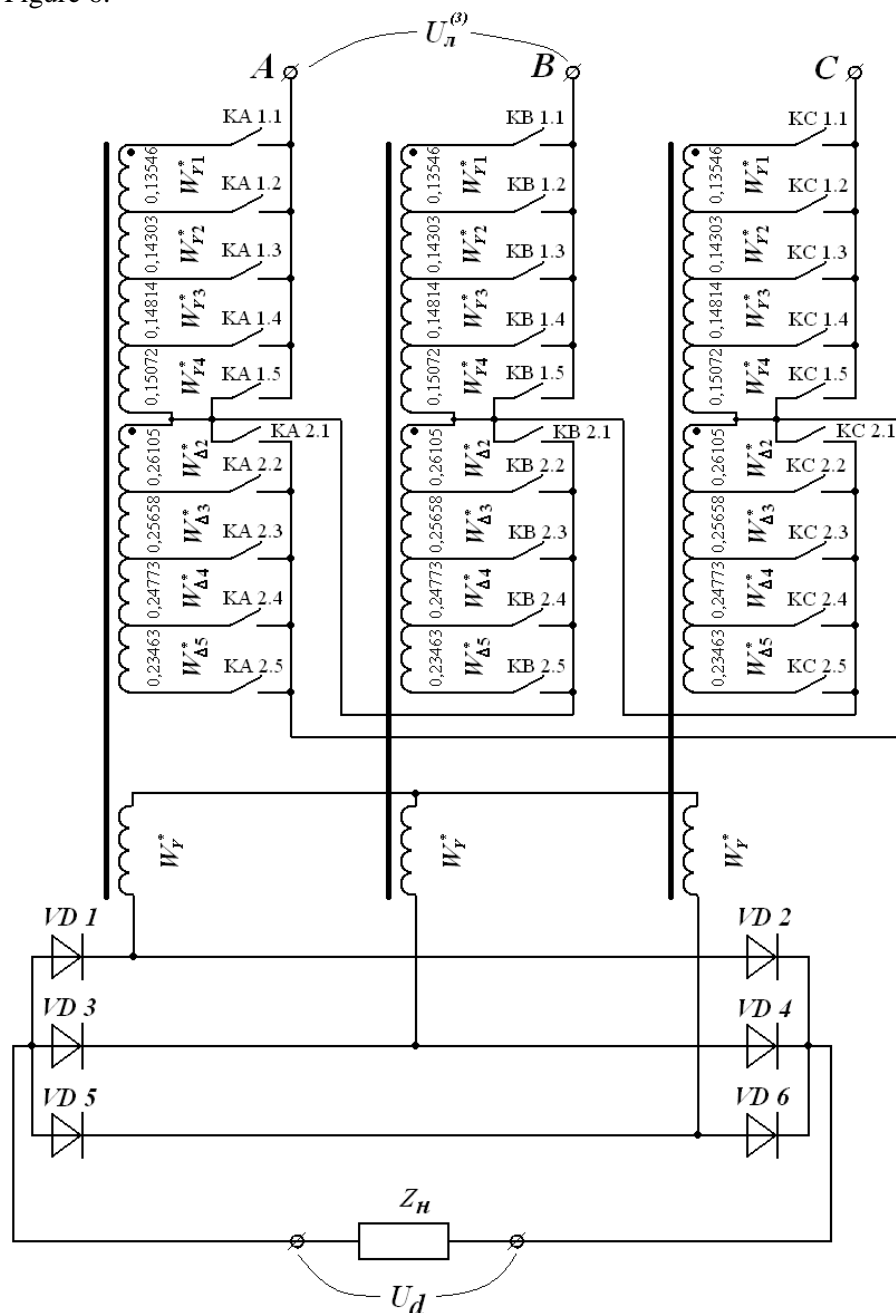


Figure 6. Schematic diagram of a six-pulse adaptive rectifier based on PhSTC “sliding delta” primary windings and the possibility of a five-stage phase shift.

Switching of the taps is carried out by synchronously working contact groups. For the A phase, these are KA1.i and KA2.i; for the B phase these are KB1.i and KB2.i, and for the C phase these are KC1.i KC2. i.. For example, if it is necessary to provide a shift $\sigma = 0$, we switch on the contacts: KA1.1,KA2.1,KB1.1,KB2.1,KC1.1,KC2.1. In this case primary windings form a “star” connection which provides mutual shift between the primary and the secondary systems of three-phase voltages equal to 0.

A tracking microprocessor system for such device based on preliminary harmonic analysis will be able to select the necessary combination of closed states of contact groups corresponding to the most rational mode of compensation of high harmonics of currents in the three-phase supply system.

The advantage of this circuit solution is the possibility of the further increasing pulse rate rectification. For example, the pulse number increase up to 12 is easily provided by a second system of the secondary windings connected in delta and an additional rectifier bridge connected in output in series or in parallel with the existing bridge based on diodes VD1-VD6.

4. Test results by simulation in the Simulink environment of the MATLAB package

The concept of the program of experiments involves the creation in the simulation environment a power part of the adaptive rectifier of Figure 6, which is powered by a three-phase AC network, which has its own internal resistance [13]. Another non-linear load is connected to the common power buses parallel to this rectifier, for example, a conventional unregulated three-phase rectifier.

It is required to perform a harmonic analysis of the supply voltages and consumed currents and empirically establish a combination of rational taps, providing the best mutual compensation of high harmonics currents of these rectifiers, confirming the technical possibility of reducing the negative influence of working rectifiers on the supply network.

For the mode found, it is necessary to empirically establish a partial improvement of the voltage waveform of the three-phase supply network. When compiling the model, generally accepted assumptions were used that idealized the rectifier switching process in order not to complicate further comparative analysis of the compensation process by the adaptive rectifier of the high harmonics of the current in the supply network. For this reason, the active natures of the values of typical three-phase network resistances and rectifier loads were adopted [14].

Figure 7 shows the fragments of the model illustrating the differences in the connection schemes of taps for switching modes of PhSTC operation and changing the phase shift from $\sigma = 0^0$ to $\sigma = 30^0$.

The principal attainability of the compensation of current high harmonics in the model is ensured by the adoption of equal powers of the nonlinear load and the adaptive rectifier.

The first series of experiments was carried out under the condition that the adaptive rectifier does not create a phase shift with respect to a system of voltages supplying a nonlinear load and $\sigma = 0^0$. In this case, two nonlinear loads in the form of rectifiers with similar parameters and character turned out to be connected to the common power buses. The currents of these loads (Figure 8, a) have the same effect on the three-phase network, distorting the shape of the supply voltage curve (Figure 9, a). Similar modes are typical for real cases with a large number of loads.

The conducted harmonic analysis showed the degree of negative influence of this mode on the wave-form of supply voltages and their harmonic composition (Figure 10, a, table 3) making the quantitative assessment of nonlinear distortions using a widely applied dimensionless coefficient Total Harmonic Distortions (THD) [15]:

$$THD_{U,I} = \sqrt{\frac{\sum_{i=2}^{\infty} A_i^2}{A_1^2}}, \quad (14)$$

where A_i – the effective values of voltages or currents of i -x harmonics.

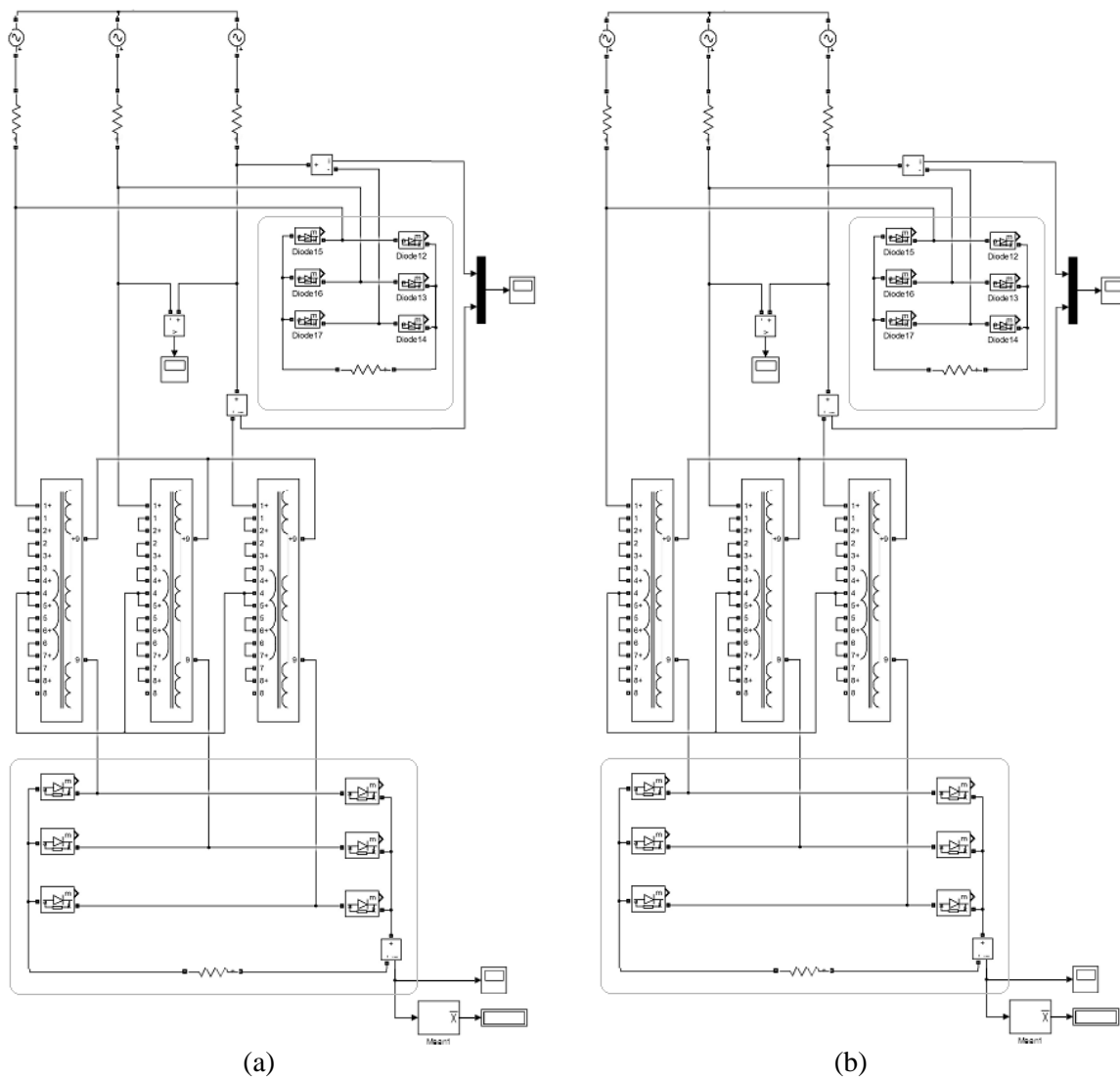


Figure 7. Fragments of models for the study of the nature of the interactions of rectifiers when changing the phase shifts: (a) the shift is zero; (b) the shift is 30°.

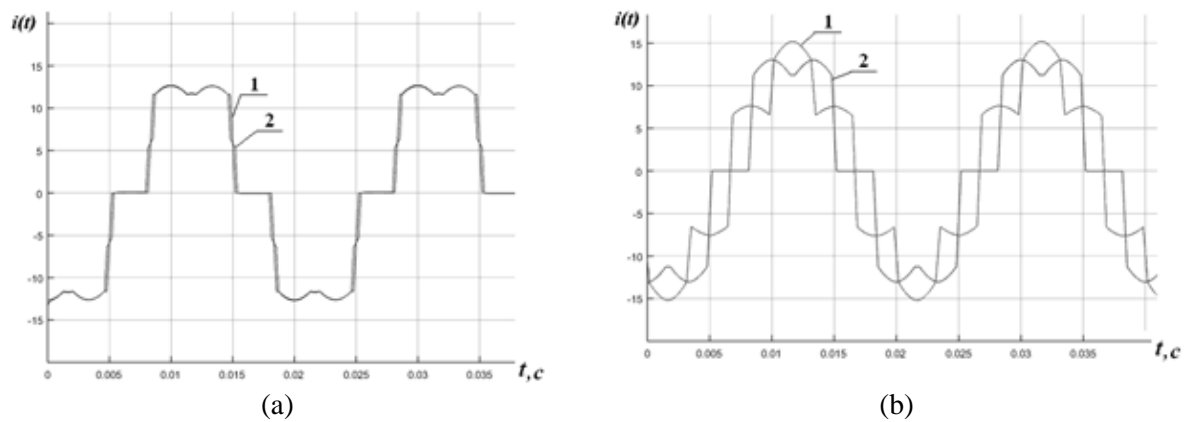


Figure 8. The curves of the currents of the adaptive rectifier – 1 and nonlinear load – 2 when the phase shifts (a) is zero; (b) is 30°.

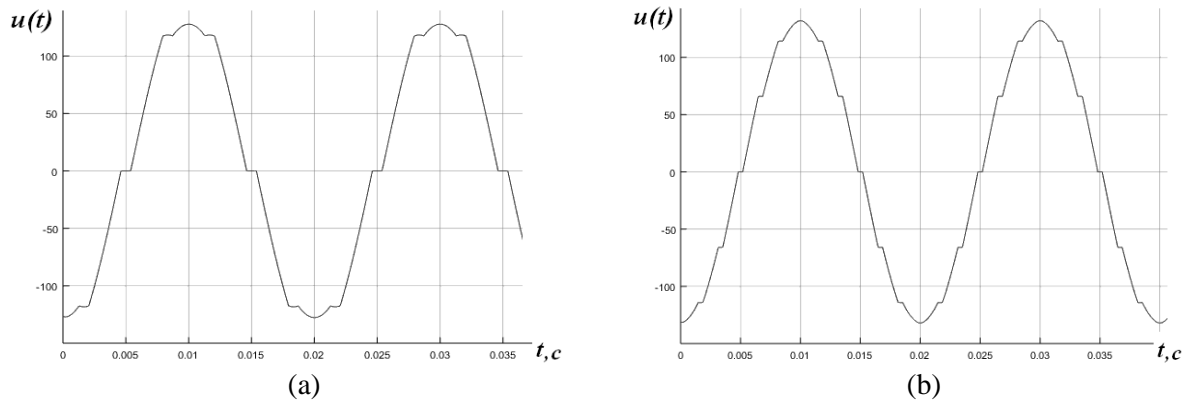


Figure 9. The waveform of the supply voltages on the common tires when the phase shifts: a is zero; b is 30° .

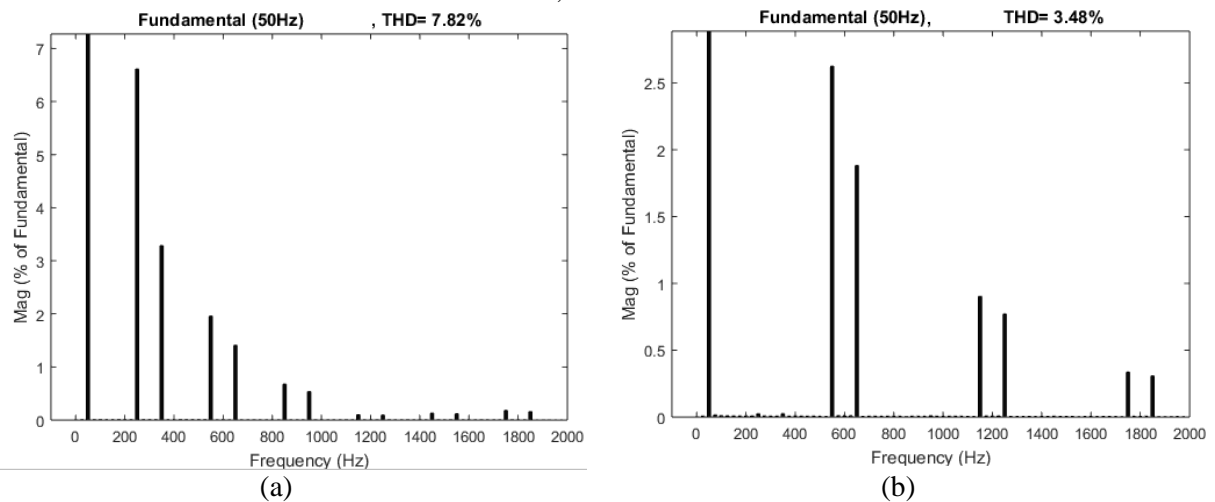


Figure 10. Harmonic composition of supply voltage on the common tires when changing the phase shifts: a – zero; b – 30° .

Table3. The harmonic composition of the voltage on the common tires

mode $\sigma = 0^\circ$, THD = 7.82%			mode $\sigma = 30^\circ$, THD = 3.48%		
Harmonic number	Value, %	Phase, degree	Harmonic number	Value, %	Phase, degree
1	100	0	1	100	0
5	6.6	180	5	<0.02	-
7	4.3	1.1	7	<0.02	-
11	1.97	1.05	11	2.02	-0.3
13	1.41	181	13	1.88	179.4
17	0.68	-1.95	17	<0.01	-
19	0.53	-0.2	19	<0.01	-
23	0.1	-3.3	23	0.9	-0.3
25	0.09	-181.7	25	0.77	179.2
29	0.13	-0.1	29	<0.005	-
31	0.12	-183.5	31	<0.005	-

In the next series of experiments, the effect of the shift σ on the THD value of supply voltages is investigated. It is established that the THD index is maximum in the mode $\sigma = 0$ and in this model

can reach the values of 7.82%. However, as soon as σ increases, the compensation of high harmonic currents of the simulated loads starts to manifest and amplify.

The maximum compensation effect is observed for the mode $\sigma = 30^\circ$ in which the number of stages in the curve of the total load current on the common tines is doubled, which is clearly seen in Figure 8b. As a result, the shape of the curve of the resulting current contains 12 steps instead of 6 and is approaching a sine that to a lesser extent had a distorting effect on the shape of the supply voltage (Figure 9b). This is quantified during the harmonic analysis (Figure 10b), which establishes that in this THD mode the value reduces to 3.48%, which is 2.24 times less than the same value defined for the original mode. Table 3 analysis shows that there is a partial compensation of high harmonics and there are harmonics, characteristic of the mode with better electromagnetic compatibility and a larger number of ripples.

In arbitrary modes, the relative shift of three-phase voltage systems, supplying nonlinear loads, in different sections of the power supply system may vary. In these cases, the best compensation effect will be achieved at intermediate stages characterizing the shift σ of the PhSTC in the range $0^\circ < \sigma < 30^\circ$. The algorithm based on the results of the harmonic analysis of the supply voltage curves to carry out automatic search of the most effective working stage of the PhST and the optimal number of such stages can be the subject of a separate study.

5. Conclusion

This work considers the possibility of using the proposed technical means, which allows ensuring the electromagnetic compatibility of loads in three-phase AC networks by creating phase shifts in the supply voltage systems and the resulting partial compensation of high harmonic currents.

For this purpose, it is proposed to use the connection scheme of the transformer windings in the “sliding delta” as the most effective from the position of minimizing the typical capacity of the transformer windings to create phase shifts. For such schemes, the maximum thermal capacity of the windings does not exceed 1.035, while widely known for such purposes, the winding connection schemes in the “zigzag” require an increase in the typical capacity to 1.15 times. To create phase shifts of the system voltages, the paper presents a universal expression linking the number of turns of the windings of a multistage PhSTC with the connection of the windings in the “sliding delta”.

We developed and proposed in this paper the concept of the circuit solution of adaptive multi-pulse rectifier based on PhSTC with the connection of windings in the “sliding triangle”, according to the authors, will improve the electromagnetic compatibility of non-linear loads, in particular, rectifiers in three-phase AC networks.

The paper presents the results of studies conducted on simulation models as evidence of the effectiveness of the proposed concept. These studies have proved the principal possibility of improving electromagnetic compatibility in three-phase AC networks. The model experiment showed that the proposed technical tool allows reducing the level of high harmonics and improving the shape of the voltage curve of the supply network, which is characterized by a decrease of THD index more than 2 times. Moreover, the results can be useful in the development of tracking microprocessor systems for the creation of modern adaptive power supplies of nonlinear industrial loads.

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