Synthesis of multi-phase zone rectifiers with coupled voltage systems

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Abstract. The capabilities of simple positions of the structural synthesis method are demonstrated by the example of creating a two-zone three-phase rectifier by aggregating three single-phase rectifiers taken as a basis. The further improvement of the circuit solution in accordance with the provisions of this method allowed, through the creation of an additional electrical node, making the transition from an unbound three-phase voltage system, operating in a two-zone three-phase rectifier to a six-phase coupled voltage system. This was reflected on the adjustment of the regulating characteristics of the rectifier and it improved a number of its indicators.

1. Introduction

The formalization of the problems of structural synthesis of rectifiers is associated with a huge number of combinations of fixed interconnections of power semiconductor devices (PSD) in the form of topological structures that form the basis of circuit solutions. A practical consequence of the method of structural synthesis of rectifiers is that the resulting rectifying voltages should be considered as the maximum potential differences on a topographic potential plane containing a voltage system unfolded in time, traditionally represented as a vector diagram. It is assumed that the modules of the voltage vectors are compared with the secondary windings of the transformer that form them and reflect their amplitude values.

Thus, the structural synthesis of rectifier circuit solutions is based on the use of the geometrical configuration of electrical circuits in the form of topological graphs, containing secondary windings that are combined by equivalent nodes using PSD [1]. So, the known structures of controlled alternating current rectifiers with zone-phase regulation were analyzed, new circuit solutions were obtained [2] and [3] that for the construction of three-phase rectifiers with zone-phase regulation there is a promising structure of a single-phase two-zone rectifier with rotation of secondary windings.

The paper aims to improve the circuit design of a two-zone three-phase rectifier based on the aggregation of three single-phase rectifiers and obtain a new direction of circuit solutions of three-phase alternating current (AC) rectifiers with zone-phase regulation and improved performance using the well-known structural synthesis method.
2. Theoretical analysis
The basic structure of a single-phase two-zone rectifier with rotation of secondary windings, as can be seen from figure 1 a, allows one part of the secondary windings to be used for operation in the positive half-period I, and the other - in the negative half-period II. In this case, in the positive half period I, the secondary winding works - $W_{21}$, and in the negative half period II, the secondary winding works - $W_{22}$. This solution eliminates the formation of nested switching circuits when the rectifier is operating in lower zones.

![Figure 1](image1.png)

**Figure 1.** Single-phase two-zone rectifier with rotation of secondary windings: 
a - simplified topology for building the first zone; b – base cell circuit solution

The well-known aggregation method [4] made it possible to obtain a two-zone three-phase rectifier with uncoupled three-phase circuits on the basis of the circuit design of figure 1b as can be seen from figure 2.

![Figure 2](image2.png)

**Figure 2.** Circuit diagram of the connection of the secondary circuits of a three-phase two-zone rectifier

Thus, this rectifier contains three basic cells, shown in figure 1, b. The interaction of these cells occurs on the side of the rectified current and is expressed in the fact that the largest instantaneous value of the rectified voltage, formed by one cell, will lead to the closure of the PSD of other cells in which these voltages are lower.

Figure 3 indicates: 1 and 2 - geometric locations of potentials (in the form of circles), which determine relative to the common point of rotation O the amplitude of the rectified voltages for the first $u_m^{(1)}$ and second zones $u_m^{(2)}$ respectively. Therefore, the radius of circle 1 is defined as $R = u_m^{(1)}$, and the radius of circle 2 according to the condition of the rectifier in the second zone corresponds to $2R = u_m^{(2)}$. In the process of rotating the elements in figure 3, which determine the rectifier's operation in the second zone, the resulting voltage produced by these elements decreases, which is reflected by the projections on the axis $u(t)$. It is obvious that the arrangement of the elements in figure 3 characterizes the extreme case when the resulting voltage created by the secondary windings $W_{21}^A$ and $W_{22}^A$ phase A, will not exceed the voltage value of the first zone created by the next winding vector $W_{22}^C$. Consequently, the discovery at this time point of the thyristor $V_{3A}$, which is responsible for the formation of one
working cycle of the second zone, will not lead to an increase in the value of the rectified voltage relative to the first zone. Thus, this point in time corresponds to the maximum delay at which the average value of the rectified voltage for the second zone will be the smallest.

Figure 3. A fragment of the simplified topology of the secondary circuits of a three-phase two-zone rectifier in the state of natural commutation during the transition from the second to the first zone

In order to define maximum delay values, according to figure 3, a right-angled triangle using 2RDO points is constructed (Fig. 4).

Figure 4. Determination of the angles of the maximum delay of opening the PSD

From the conditions of constructing elements on the topographic potential plane, it follows that the sides of the triangle $2R - D = u_m^{(1)}$, $2R - O = 2u_m^{(1)}$. Hence:

$$\beta = \arcsin \left( \frac{u_m^{(1)}}{2u_m^{(1)}} \right) = 30^0, \quad (1)$$

$$\alpha = 180^0 - \beta = 150^0.$$

Thus, the value of the maximum delay of the opening of the PSD in the second zone is determined by the angle $\alpha = 150^0$.

If three-phase multi-zone (N - is the number of zones) rectifiers are built in this circuit direction, then the lengths of the triangle sides in Figure 5 will be written as follows: $2R - D = (N - 1) \cdot u_m^{(1)}$, $2R - O = N \cdot u_m^{(1)}$, and the angles that determine the maximum delay of the opening of the PSD will be:

$$\alpha = 180^0 - \beta = 180^0 - \arcsin \left( \frac{N - 1}{N} \right). \quad (2)$$

Therefore, for a three-phase rectifier, the maximum delay value of the opening of the PSD for large numbers $N \rightarrow \infty$ zones will tend to value $\alpha = 180^0 - \arcsin(1) = 90^0$.

The lower limit of the delay in the opening of the PSD is determined by the condition of reaching
the switching mode of the secondary neighboring windings under the condition that they form equal and greatest potentials among the possible ones, as was the case for the limiting mode when $\alpha = 60^\circ$ for the first zone. Thus, in the second zone, the values of the thyristor opening delays are in the working range $\alpha \in 60^\circ...150^\circ$, and the regulation characteristic of a three-phase two-zone rectifier $U_d^* = f(\alpha)$ in relative units, taking into account the identified limits of values, will take the following form (Fig. 5).

![Figure 5. Adjustment characteristics of a three-phase two-zone rectifier with angles ranges: 1 – for the first zone $\alpha \in (60^\circ...180^\circ)$; 2 – for the second zone $\alpha \in (60^\circ...150^\circ)$; 3 – expression restriction (2)](image)

Analysis of the processes depicted in Figures 3 and 4 shows that the closure of the thyristors of the higher N zones for the three-phase multi-zone rectifiers under consideration will occur at times when the resulting voltage of the lower zones N-1 is maximum and equal to the amplitude value $U_m^{N-1}$. Moreover, the appearance of sharp-pointed pulses of currents of the second zone on the sinusoidal peaks of the currents of the first zone forms not the most optimal figure in terms of energy indicators, forms factors and harmonic composition [4].

3. Results and Discussion
The improvement of the three-phase rectifier operating modes in the older $N > 1$ zones with delay angles for PSD opening close to maximum values (for the second zone this value $\alpha \rightarrow 150^\circ$), as shown by the provisions of the structural synthesis method, can be achieved by switching from an unrelated three-phase voltage system to an associated six-phase voltage system [5,6].

The connection of the three-phase system of voltages into a six-phase system is carried out by creating a common electrical node, which will unite the central points of the secondary winding parts of all phases and act as the center of rotation of the resulting winding vector system on the topological potential plane (Fig. 6).
**Figure 6.** Creating a connected six-phase system: 

- а – system of rotating winding vectors on a topological potential plane; 
- б – combinations of levels of linear voltages relative to one pole; 
- в – the process of building a schematic solution for the first zone.

This simple circuitry step opens up a new direction for building multi-zone three-phase rectifiers using for their operation combinations of different levels of line voltages of a six-phase system. In this case, instead of a system of resulting voltages with amplitudes \( u_m^{(1)} \) and \( u_m^{(2)} = 2u_m^{(1)} \) and mutual phase shifts \( \pm \pi/3 \), the resulting structure in fig. 8, а will create a six-phase system with three levels of line voltages \( u_1 = u_m^{(1)} \), \( u_2 = \sqrt{3} \cdot u_m^{(1)} \) and \( u_3 = 2 \cdot u_m^{(1)} \) relative to each pole (fig. 6, б). This combination of voltage levels and their phase shifts eliminates the closure of the rectifier thyristors at those times when the projection of the nearest vector of the neighboring phase determines the amplitude value of the resulting voltage. This makes it possible to carry out PSD switching under the condition of equality of linear voltages \( u_1 \) and \( u_1' \) or \( u_2 \) and \( u_2' \) of the neighboring phases when the rectifier operates on higher \( N > 1 \) zones.

The concept itself undergoes minor changes (Fig. 7).

**Figure 7.** Circuit diagram of the connection of the secondary three-phase two-zone rectifier circuits.

If the opening delay of the thyristor VS3C is less than the angle \( \alpha_s = 120^\circ \), in the circuit of the current flow, load with open PSD will be the voltage of the secondary windings, forming the magnitude of the greatest linear voltage \( u_3 = 2 \cdot u_m^{(1)} \).

Such a transition from line voltage \( u_2 = \sqrt{3} \cdot u_m^{(1)} \) to line voltage \( u_3 = 2 \cdot u_m^{(1)} \) will change the shape of the curve of the rectified current, and the value of the average rectified voltage in this mode at \( \alpha_s \in (60^\circ...120^\circ) \) will be determined as:

\[
U_d = \frac{2}{\pi} u_m^{(1)} \cos \left( \alpha_s - \frac{\pi}{3} \right) + 1.
\]  

Expression (3)

Expressions allow constructing the adjustment characteristic in relative units \( U'_d = f(\alpha) \) of a six-phase two-zone rectifier for the ranges of found values \( \alpha \) (fig. 8).
Figure 8. Adjusting characteristics of a six-phase rectifier with angles ranges: 1 – for the first zone $\alpha \in (120^0...180^0)$; 2 – for the first zone $\alpha \in (60^0...120^0)$; 3 – for the second zone $\alpha \in (120^0...180^0)$; 4 – for the second zone $\alpha \in (60^0...120^0)$

As the analysis shows, the advantage of the obtained structure of a six-phase rectifier appears when operating with large opening delay angles of PSD, at which sharp-pointed impulses are formed belonging to senior zones.

4. Conclusion
The possibilities of the structural synthesis method are shown, as a result of which, by aggregating three single-phase rectifiers, a three-phase zone-phase rectifier circuit with an unrelated three-phase voltage system was obtained and the specifics and its operation principle in each zone were described.

Analytical expressions are obtained for determining the maximum delay of the opening of the PSD rectifiers with an unbound three-phase voltage system and it has been established that if the maximum delay in the first zone is $180^0$, then in the second zone it will be limited and will be only $150^0$. In common case this delay for the zone N will be determined by the expression $\alpha = 180^0 - \arcsin \left( \frac{N-I}{N} \right)$, that for the number of zones $N \to \infty$ will limit the operating range of delays $\alpha \in (60^0...90^0)$.

To improve multi-zone rectifiers a new direction of ways has been identified, which consists in linking multiphase systems in such a way that a common electrical node is formed on the topographic potential plane, which can act as the center of rotation of a multiphase winding vector system with different levels of line voltages. In this case, the combination of the obtained levels of line voltages expands the operating range of the delays of the opening angles of the PSD to the values $\alpha \in (60^0...90^0)$ and helps to improve the shape of the curve of rectified voltages and currents.

Acknowledgment
The paper has been prepared with the support of the Ministry of Education and Science of the Russian Federation, grant № 8.10997.2018/11.12.

References
[1] Ivanov V V, Myatezh S V, Shchurov N I, Atabaeva L S 2017 Improvement of single-phase alternating rectifiers by structural synthesis method In Proc. of the 18th International conference of young specialists on micro/nanotechnologies and electron devices (EDM 2017) (Novosibirsk : NSTU) pp. 551 – 555
[2] Ivanov V V, Myatezh S V, Kapustin A V Alekseeva I K 2017 Improvement of controlled rectifiers with zone-phase regulation by the method of structural synthesis In Proc. of The 14th International Scientific-Technical Conference APEIE (Novosibirsk : NSTU) pp. 75 – 78.
[3] Rozanov Yu K, Ryabchitsky M V, Kvasnyuk A A 2009 Power electronics (Moscow: Publishing House MEI)
[4] Zinovyev G S 2003 Power Electronics Basics (Novosibirsk : NSTU)
[5] German-Galkin S G 2013 Virtual laboratories of semiconductor systems in the environment Matlab-Simulink (Mocsow: Publishing House Lan)
[6] Plaks A V 2005 Control systems of electric rolling stock (Moscow: Training Center for Education in rail transport).
[7] Evdokimov S A, Zinovyev G S 2008 Rectifiers classification option per topological features In Proc. of IXth International Conference Proceedings Current issues of electronic instrument making vol. 7 (Novosibirsk: NSTU) pp 3-14.
[8] Evdokimov S A, Shchurov N I 2010 Structural synthesis of multi-phase valve inverters (Novosibirsk: NSTU Publisher)
[9] Bessonov L A 1999 Theoretical foundations of electrical engineering. electrical circuits (Moscow: Gardariki)
[10] Klimov V P 2007 Modern directions of the development of AC power converters Practical power electronics 25 43-51