Study of switching processes in the zone rectifier with a fractional number of zones

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Abstract. This work is devoted to switching processes which take place in zone rectifiers with a fractional number of zones. Methods of structural synthesis are implemented to analyze switching processes occurring in rectifiers circuits. By means of the considered circuits program modelling it is shown that structural synthesis method application allows not only making an effective directed search of improvements for circuits but also making the efficiency analysis during the search process.

1. Introduction

The use of structural synthesis principles is a proven tactic for improving and obtaining new circuit solutions in the field of controlled rectifiers.

This method is based on the use of electrical circuits’ geometric configuration in the form of topological graphs containing secondary windings. The windings are combined by equivalent nodes using PSD [1]. Such circuits as [2] and [3] were obtained by means of the structural synthesis method.

2. Analysis of a two-zone three-phase rectifier switching processes

The commutation processes in the well-known two-zone three-phase rectifier obtained by the aggregation method [4] with unbound three-phase circuits (Figure 1) will be considered.

![Figure 1. Three-phase two-zone rectifier principal scheme.](image)

The interaction of different zones for each phase can be analyzed on the topographic potential plane by placing the vectors of the corresponding secondary voltages compared to the transformer secondary windings that form them. Figure 2. Shows that for the first zone, control is implemented by thyristors VS2A, VS2B, VS2C. Obviously, opening delay of the only PSD in the contour, where at the moment the angle $\alpha_1$ of the secondary winding positive polarity rotating voltage vector is in the range from 120° to 180°, creates such a mode of operation that the load current $Z_d$ has time to reach zero.
This mode of operation ensures the natural close of the corresponding thyristor in the contour and the load current will be intermittent (Figure 2,b).

If the value of the PSD opening delay is reduced to such value that at a given moment of time, angle $\alpha_2$ of the secondary winding positive polarity rotating voltage vector will be in the range from $60^\circ$ to $120^\circ$, then the operation mode with the continuous nature of the load current $Z_d$ will be reached. Fact that operation mode with continuous nature of the load can be reached becomes obvious from Figure 2,a, because when the rotating vector of the winding voltage connected on the topographic potential plane with the diode $VD_{2A}$ approaches the angle of $180^\circ$, its place become taken by the next winding voltage vector with the diode $VD_{1C}$. This requires, due to the equality of working intervals $2\pi/6 = 60^\circ$, the next PSD opening for the current flow, which leads to early close of the thyristor $VS_{2A}$ before the point at which the load current $Z_d$ could reach zero (Figure 2,c). If the PSD opening delay value allows the secondary voltage vector to reach an angle $\alpha_2$ equal to $60^\circ$, then the PSD switching mode borderline will be reached. It is characterized by equal and maximal potentials of the neighbor secondary windings, out of the set of possible for the given zone. They form the facets of the common sector on the topographic potential plane, which will be identical to the operation mode of the three-phase uncontrolled rectifier with 6 rectified voltage pulsations (Figure 2,d). Further reduction of the PSC opening delay value does not make sense.

![Figure 2](image-url)

**Figure 2:** Three-phase rectifier in the first zone: a – formation of rectified voltage at switching of PSD; b, c, d – curves of secondary voltages and load current at delays of PSD opening, respectively, $\alpha_1 \in (120^\circ...180^\circ)$, $\alpha_2 \in (60^\circ...120^\circ)$ and $\alpha_2 = 60^\circ$.

The thyristors $VS_{1A}$, $VS_{3A}$, $VS_{1B}$, $VS_{3B}$, $VS_{1C}$, $VS_{3C}$ are provided to control the three-phase rectifier in the second zone. In order to set the opening delay values ranges for these thyristors, it is necessary to determine the maximum delay value, at which the average rectified voltage for the second zone will be the smallest possible. For this purpose, on the topographic plane the elements of the rectifier electrical circuits in the form of rotating windings-vectors are placed. These elements are used in the second zone and form a temporary connection by switching the PSD. Figure 3a shows the process of opening at $\alpha = 140^\circ$ and following closing of thyristor $VS_{3A}$ of the second zone, at the moment...
At this moment of time, the nearest neighbor vector of the resulting voltage in first zone determines the amplitude value \( u_m(t) = u_m^{(1)} \).

This circumstance characterizes the shape specificity of the load current curve (Figure 3b).

![Figure 3](image-url)

**Figure 3.** Load current formation by a three-phase rectifier on the second zone: a – switching process of PSD at interaction of voltages of the first and second zones; b, c, d – resulting load currents for values \( \alpha = 140^\circ \), \( \alpha = 125^\circ \) and \( \alpha = 70^\circ \) respectively.

3. **Analysis of the improved two-zone three-phase rectifier switching processes**

The improvement of the three-phase rectifier operation mods with the number of zones \( N > 1 \) and delay angles close to the maximum values (for the second zone this value is \( \alpha \rightarrow 150^\circ \)), as principles of the of structural synthesis method show, can be achieved due to transition from the unbound three-phase voltage system to the associated six-phase voltage system [4].

Transition from the three-phase voltage system to the six-phase system is carried out by creating a single electrical node that unites the central points of the secondary windings of all phases and serves as the rotation center for resulting vector windings system on the topological plane, as it described in [5]. This simple schematic step opens a new direction for the multi-zone three-phase rectifiers design using different levels combinations of the six-phase system linear voltages for their work. The concept itself got only minor changes (Figure 4).

![Figure 4](image-url)

**Figure 4.** Improved Three-phase two-zone rectifier principal scheme.

Work in the first zone is determined by the obvious interaction of PSD and winding-vectors on the topological potential plane and it is similar to the rectifier from Figure 2,a. If the delay in thyristor
opening assumed to be $\alpha_t \in (120^0...180^0)$, the discontinuous form of currents as in Figure 2,b is obtained. The value of the average rectified voltage in this mode is

$$U_d = \frac{1}{2} \int_0^{\frac{2\pi}{6}} u(t)dt = \frac{3}{\pi} u_m^{(1)} \cos \left( \frac{\alpha_t - \frac{2\pi}{3}}{\frac{1}{2}} \right)$$  \hspace{1cm} (1)$$

If the opening delay of another thyristor is in the range of $\alpha_z \in (60^0...120^0)$, it can be closed only if condition of voltages equality $u_m^{(1)} = u_1$ is fulfilled. Thus, thyristor VS_{1B} closes at the moment $\omega t = 120^0$. In this case, the form of load currents is continuous, as in Figure 2, c, and the value $U_d$ in this mode is

$$U_d = \frac{1}{2} \int_0^{\frac{2\pi}{6}} u(t)dt = \frac{3}{\pi} u_m^{(1)} \sin \left( \frac{\alpha_z + \frac{\pi}{6}}{\frac{1}{2}} \right)$$  \hspace{1cm} (2)$$

In the border-line case, if the delay is $\alpha = 60^0$, opening and closing of thyristors in the first zone take place at those moments of time when the voltages of neighbor-phases are equal. The shape of load currents in this case corresponds to one shown in Figure 2,d, and the value $U_d = \left(\frac{3}{\pi}\right) u_m^{(1)}$ can be determined from expression (2).

The switch of the six-phase rectifier to the second working zone is made by switching from phase voltages to linear voltages. This is achieved by additional connection of rotating windings-vectors located at the bottom of the topographic potential plane to the power supply circuit by means of PSD. Since the associated six-phase system has linear voltages with different levels, if a smooth increase in value $U_d$ is required, thyristors should be connected with appropriate time delays: linear voltage $u_z = \sqrt{3} \cdot u_m^{(1)}$ first, and then $u_z = 2 \cdot u_m^{(1)}$.

Figure 5 shows the border-line angles of individual windings-vectors rotation on the topological potential plane during the six-phase rectifier work with linear voltage $u_2$ in the second zone. As can be mentioned, the location of rotating windings-vectors not only determines the value of the resulting linear voltage, but also in accordance with the angles of rotation, sets the permissible range of time delays in the opening of rectifier thyristors.

**Figure 5.** The use of linear voltage $u_2$ by a six-phase rectifier on the second zone at various windings-vectors rotation angles: a – linear voltage maximum $u(t) = \sqrt{3} \cdot u_m^{(1)}$; b – linear voltage minimum $u(t) = \sqrt{3}/2 \cdot u_m^{(1)}$.

Thus, for example, the minimum delay of VS_{3C} thyristor opening corresponds to an angle $\alpha_z = 120^0$, and the maximum should not exceed $\alpha_z = 180^0$. In this range, the resulting voltage, supplied to the load $Z_d$, is determined by the work of two winding voltages $W_{22}^B$ and $W_{22}^C$, taking into account the designations in Fig. 10 and the polarity of their connection.
\[ u(t) = u_n(t) - u_z(t) = u_m^{(1)} \sin \left( wt \cdot \frac{2\pi}{3} \right) - u_m^{(1)} \sin \left( wt \cdot \frac{4\pi}{3} \right) \] (3)

**Figure 6.** Load current formation by a six-phase rectifier in second zone: a - switching process of PSD at interaction of phase voltage \( u_m^{(1)} \) of the first and linear voltage \( u_z \) of the second zone; b, v, g - resulting load currents for values \( \alpha = 175^\circ \), \( \alpha = 150^\circ \), and \( \alpha = 120^\circ \).

**Figure 7.** Six-phase rectifier's on the second zone at \( \alpha_4 < 120^\circ \): a – creation of a load \( z_d \) feed circuit voltage \( u_3 = 2 \cdot u_m^{(1)} \); b – a fragment of a load current curve at switching of linear voltages \( u_2 \) and \( u_3 \) with a delay \( \alpha = 115^\circ \); c, d, e – resultant currents of loading at, \( \alpha = 115^\circ \), \( \alpha = 90^\circ \) and \( \alpha = 60^\circ \).
Before opening of the thyristor VS3C in Fig.10, a, at the rectifier output there is a phase voltage \( u_s(t) \) supplied to the load through the diode VD, which determines the shape of the voltage curve as in Fig.3, g, corresponding to the operation mode in the first zone.

It determines the formation of the six-phase rectifier rectified voltage curve (Figure 6), operating at the second zone with a delay of thyristor opening in the range \( \alpha_3 \in (120^0...180^0) \).

Value of average rectified voltage in this mode \( \alpha_3 \in (120^0...180^0) \) is

\[
U_d = \frac{3}{\pi} u_m^{(1)} \left[ 2 - \sqrt{3} \sin \left( \frac{\alpha_3 - \frac{2\pi}{3}}{\frac{\pi}{3}} \right) - \cos \left( \frac{\alpha_3 - \frac{\pi}{3}}{\frac{\pi}{3}} \right) \right]
\]  
(4)

In case the delay of thyristor VS3C opening is less than an angle \( \alpha_3 = 120^0 \), in the load current circuit with open PSD, there are secondary windings voltages forming the value of the largest linear voltage \( u_s = 2 \cdot u_m^{(1)} \). The range of thyristor opening delay variation in this mode can be seen from Figure 7, a, it is \( 60^0 < \alpha_d < 120^0 \).

Such transition from linear voltage \( u_2 = \sqrt{3} \cdot u_m^{(1)} \) to linear voltage \( u_3 = 2 \cdot u_m^{(1)} \) will change the shape of the rectified current curve (Figure 7, b), and the value of the average rectified voltage in this mode \( \alpha_4 \in (60^0...120^0) \) can be determined with expression:

\[
U_d = \frac{3}{\pi} u_m^{(1)} \left[ \cos \left( \frac{\alpha_4 - \frac{\pi}{3}}{\frac{\pi}{3}} \right) + 1 \right]
\]  
(5)

The results of calculation in the Simulink simulation environment [7] have shown that the level of the higher harmonics determined by the THD value for the curve in Figure6,b is 1.7 times lower than for a similar curve in Figure 7, b, provided that the average values for these curves are the same. A similar conclusion can be drawn by comparing the form coefficients of these curves, which differ by 1.5 ... 1.7 times for rectifiers with large delay angles. As the delay angles decrease, these differences decrease as well.

4. Conclusion

The methods of structural synthesis were implemented to analyze the switching processes in rectifiers circuits. By means of the considered circuits program modeling it was shown that the structural synthesis method application allows not only making effective directed search of improvements for circuits, but also making the efficiency analysis during the search process. It was found that the level of currents higher harmonics in improved two-zone rectifier with a six-phase voltage system, during the work process with large values of delays in the PSD opening angles, is 1.7 times lower than for a two-zone three-phase rectifier in similar conditions.

References

[1] Evdokimov S A 2010 Structural synthesis of multiphase valve transducers(Novosibirsk: NSTU)
[2] Ivanov V V, Myatezh S V, Kapustin A V and Alekseeva I K 2017 Improvement of controlled rectifiers with zone-phase regulation by the method of structural synthesisIn Proc. of the 14th International Scientific-Technical Conference APEIE(Novosibirsk: NSTU) pp 75 – 78
[3] Rozanov Yu K 2009 Power electronics: university textbook(Moscow: Publishing House MEI)
[4] Zinovyev G S2003 Power Electronics Basics 2nd ed(Novosibirsk: NSTU)
[5] Ivanov V V, Myatezh S V and Rozhkova M V 2019 Synthesis of multi-phase zone rectifiers with coupled voltage systemsJournal of Physics: Conference Series1333062008
[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 Rectifiers classification option per topological featuresCurrent issues of electronic instrument making:IXth International Conference Proceedings Novosibirsk: NSTU vol 72008 pp 3-14.
[7] German-Galkin S G2013 *Virtual laboratories of semiconductor systems in the environment Matlab-Simulink* (Moscow: Publishing House Lan)

[8] Nikolsky V V *Theory of the electromagnetic field* 1964 (Moscow: Higher school)