Synthesis of devices for efficient energy conversion

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Abstract. The synthesis of devices for efficient energy conversion is shown. It is shown that simple aggregation as the most obvious way to obtain three-phase converters based on single-phase circuit solutions can lead to disadvantages during their operation. The article demonstrates some techniques of the method of structural synthesis, which made it possible to improve the circuit design of a three-phase rectifier with zone-phase regulation and improve the shape of the rectified current curve.

1. Introduction

It is known that with a simple aggregation of already known circuit solutions in order to obtain new converter circuits, the potential capabilities of the new structure synthesized in this way are not taken into account. Thus, three-phase AC rectifiers obtained by simple aggregation of single-phase AC rectifiers do not always immediately have the best technical and economic indicators [1].

The task is to improve the shape of the rectified voltage curve of a three-phase controlled rectifier, built by aggregating three single-phase controlled rectifiers with secondary windings divided into several working zones.

2. Methods

The work is supposed to use the method of structural synthesis, which considers the geometric configuration of electrical circuits of an alternating current rectifier with a frequency formed from transformer windings and power semiconductor devices (PSD) in the form of topological graphs [1]. The voltages that induce the transformer windings are represented in the form of vectors rotating at a speed of $\omega = 2\pi \cdot f$ on the topographic potential plane, and the modules of the voltage vectors themselves are compared with the transformer windings that form them. In this case, the voltage systems rotating in the form of a vector diagram and the windings associated with them can participate in the formation of the resulting rectified voltage, determined through the projection of the maximum potential differences.

Since simple aggregation combines three single-phase rectifiers on the rectified current side, in the resulting three-phase rectification circuit, the three-phase circuits themselves will be unconnected. The interaction between the elements of circuits of different phases in such a circuit is possible only from the side of the rectified voltage, and the number of working combinations of the maximum potential differences in the resulting rectified voltage will be limited. To improve the shape of the rectified voltage curve, it is necessary not only to determine the missing combinations of voltages on the
topographic potential plane, but also the methods of obtaining them by analyzing the available combinations of connections of three-phase circuits by means of PSD.

3. Result of simple aggregation
With a decrease in the average voltage at the output of a phase-controlled rectifier, the power factor decreases, therefore the entire regulation range is often divided into separate zones, dividing the secondary winding of the rectifier into parts for this. All parts of the winding work in the older zones, only some of them work in the lower zones. In [2], it is shown that a single-phase rectifier with rotation of the secondary windings excludes the formation of nested switching circuits when operating in lower zones, since one part of the secondary windings in this case is used for operation in a positive half-cycle, and the other part - in a negative half-cycle.

A controlled three-phase rectifier can be built from three such rectifiers by simple aggregation (Fig. 1).

\[ \text{Figure 1. Synthesis of a three-phase rectifier on the topological potential plane} \]

\[ \text{a; curves of secondary voltages and load currents during delays in opening the PSD} \]

\[ \text{b; with delays in opening PSD} \]

\[ \text{c} \]

In the lower zone, control is implemented by thyristors VS\textsubscript{2A}, VS\textsubscript{2B}, VS\textsubscript{2C} (Fig. 3, a) in the role of controlled PSD. Considering \( Z_4 = R_4 \) in the first approximation, the delay in the range from 120\(^\circ\) to 180\(^\circ\) of the opening of the PSD will create an operation mode with an intermittent nature of the load current (Fig. 3, b). If we reduce the value of the delay in opening the PSD within the range from 60\(^\circ\) to 120\(^\circ\), then the operating mode with a continuous nature of the load current \( Z_d \) will be achieved. In this mode, for example, the place of the winding voltage vector rotating and approaching the 180\(^\circ\) angle, connected in Fig. 1, a with the VD\textsubscript{2A} diode, will be occupied by the next winding voltage vector with the VD\textsubscript{1C} diode. Due to the equality of the working intervals \( 2\pi/6 = 60^\circ \), the opening of the next PSD leads to the premature closure of the operating PSD, preventing the load current \( Z_d \) from reaching zero (Fig. 3, c). The opening delay of the PSD, equal to 60\(^\circ\), gives the limiting mode, which is characterized by the equal and highest potentials of the secondary adjacent windings from the set possible for the lower zone. They form the faces of the general sector on the topographic potential plane. This will be identical to the operation mode of a three-phase uncontrolled rectifier with six pulsations of the rectified voltage, and a further decrease in the value of the delay in opening the PSD is meaningless [3].

For operation in the senior zone, three single-phase rectifiers, as the basis of a three-phase rectifier, have corresponding thyristors VS\textsubscript{1A}, VS\textsubscript{3A}, VS\textsubscript{1B}, VS\textsubscript{3B}, VS\textsubscript{1C}, VS\textsubscript{3C}. On the topographic plane, there is a part of the elements of the electrical circuits of a three-phase rectifier in the form of rotating vector windings, which form temporary connections due to the switching of the PSD for operation in the senior zone (Fig. 1).
Figure 2 shows 1 and 2 – circles with a common point of rotation O as geometrical places of potentials that determine the amplitudes of rectified voltages for the lower $u_m^{(1)}$ and higher $u_m^{(2)}$ zones, respectively. The radius of circle 1 is defined as $R = u_m^{(1)}$, and the radius of circle 2 is $2R = u_m^{(2)}$. In the process of turning the elements in Fig. 2, the resulting stress created by these elements decreases, which is presented in the form of projections onto the $u(t)$ axis. The arrangement of the elements in Fig. 2 characterizes the extreme case, when the resulting voltage created by the secondary windings $A_2^{(1)}$ and $A_2^{(2)}$ phase A is equal to the value of the voltage of the lowest zone, which is created by the next winding-vector $A_2^{(2)}$. This moment in time corresponds to the maximum delay at which the average value of the rectified voltage for the senior zone will be the smallest.

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

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

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

Thus, the value of the maximum delay in the opening of the PSD in the senior zone is determined by the angle $\alpha = 150^0$. The lower limit of the opening delay of the PSD is determined by the condition for achieving the switching mode of the secondary adjacent windings, provided that they form equal and highest potentials, which is achieved with a delay $\alpha = 60^0$. Thus, in the senior zone, the thyristor opening delays are in the operating range of $\alpha \in 60^0...150^0$.

The analysis of the processes shows that the closure of the thyristors of the higher zones will occur at the moments of time when the resulting voltage of the lower zones is maximum and is equal to the amplitude value.

Fig. 3, a shows the process of opening with a delay $\alpha = 140^0$ and the subsequent closing of the thyristor VS$_{3A}$ of the high zone at the moment $\omega t = 150^0$ when the nearest neighboring vector of the resulting voltage of the low zone determines the amplitude value $u_{2c}(t) = u_m^{(1)}$.

This circumstance characterizes the specificity of the shape of the load current curve (Fig. 3, b). The appearance of sharp-pointed impulses of the currents of the senior zone at the sinusoidal peaks of the currents of the first zone does not form the most optimal figure from the point of view of the shape coefficients and harmonic composition [4].
Figure. 3. Formation of the load current in the senior zone: a - the process of switching the PSD; b, c - resulting load currents for delays $\alpha = 140^\circ$ and $\alpha = 125^\circ$, accordingly

4. Solution

The increase in the number of available combinations of voltages to obtain a rectified voltage curve contributes to the improvement of its shape [4,5]. Instead of a voltage system with amplitudes $u_m^{(1)}$ and $u_m^{(2)} = 2u_m^{(1)}$ without complicating the rectifier circuitry, you can create a six-phase system with three levels of interphase voltages, $u_1 = u_m^{(1)}$, $u_2 = \sqrt{3} \cdot u_m^{(1)}$ and $u_3 = 2 \cdot u_m^{(1)}$ and relative to each pole, if you go from an uncoupled three-phase voltage system to a coupled six-phase voltage system. With simple aggregation, this was not provided. However, it makes it possible to exclude the closure of the rectifier thyristors at those times when the projection of the nearest vector of the adjacent phase (Fig. 2) determines the amplitude value of the resulting voltage. This makes it possible to carry out the switching of the PSD when the combinations of different phase-to-phase voltages are equal during operation in the older zones.

The operation of the rectifier in the senior zone is realized due to the additional connection with the help of the PSD of the rotating windings-vectors of the coupled six-phase system, located in the lower, negative part of the topographic potential plane. Since in such system there are phase-to-phase voltages with different levels, if it is necessary to smoothly increase the value $dU$, it is necessary to connect using thyristors with appropriate time delays, first the phase-to-phase voltages $u_2 = \sqrt{3} \cdot u_m^{(1)}$, and then $u_3 = 2 \cdot u_m^{(1)}$.

Figure 4 shows the limiting angles of rotation of the vector windings on the topological potential plane when using a six-phase rectifier of the phase-to-phase voltage $u_2$ in the senior zone. The location of the rotating vector windings not only clearly determines the value of the resulting voltage, but also, in accordance with the angles of rotation, sets the permissible range of time delays for opening the thyristors.
Figure 4. The use of the phase-to-phase voltage $u_{2}$ on the senior zone at different angles of rotation of the windings-vectors: a - line voltage is maximum $u(t) = \sqrt{3} \cdot u_{m}^{(i)}$, b - line voltage is minimum $u(t) = \sqrt{3}/2 \cdot u_{m}^{(i)}$

The analysis showed that if in the younger zone the value of the average rectified voltage was formed by phase voltages and was determined:

for the range of thyristor opening delays $2\pi/3 < \alpha \leq \pi$:

$$U_{d} = \frac{1}{2}\frac{2\pi}{6} \int_{a}^{b} u(t)dt = \frac{3}{\pi} u_{m}^{(i)} \left( \cos \left( \alpha_{c} - \frac{2\pi}{3} \right) - \frac{1}{2} \right),$$

(2)

and for the range of thyristor opening delays $\pi/3 < \alpha \leq 2\pi/3$:

$$U_{d} = \frac{1}{2}\frac{2\pi}{6} \int_{a}^{b} u(t)dt = \frac{3}{\pi} u_{m}^{(i)} \sin \left( \alpha_{c} + \frac{\pi}{6} \right).$$

(3)

then on the senior zone, phase-to-phase voltages are used, determining its value of the average rectified voltage:

for the range of thyristor opening delays $2\pi/3 < \alpha \leq \pi$:

$$U_{d} = \frac{3}{\pi} u_{m}^{(i)} \left[ 2 - \sqrt{3} \sin \left( \alpha_{c} - \frac{2\pi}{3} \right) - \cos \left( \alpha_{c} - \frac{\pi}{3} \right) \right],$$

(4)

and for the range of thyristor opening delays $\pi/3 < \alpha \leq 2\pi/3$:

$$U_{d} = \frac{3}{\pi} u_{m}^{(i)} \left[ \cos \left( \alpha_{c} - \frac{\pi}{3} \right) + 1 \right].$$

(5)

This improves the shape of the rectified voltage curve (Fig. 5) of the rectifier operating under the resistive load in the senior zone.

Figure 5. Formation by the rectifier of the load current in the senior zone: a - the process of switching the PSD; b, c - the resulting load currents for delays $\alpha = 175^\circ$ and $\alpha = 120^\circ$
The advantage of the obtained structure of the rectifier is especially noticeable when working with large opening delay angles of the PSD, at which sharp-pointed pulses are formed. The results of simulation modeling [6] show that the level of higher harmonics determined through THD for the curve in Fig. 5, b is 1.7 times lower than for the similar curve shown in Fig. 3, b, provided that the average the values for these curves are the same. As the delay angles decrease, these differences decrease.

5. Conclusion
It is shown that the method of structural synthesis is able to improve the circuit design and improve the shape of the rectified voltage curve of a three-phase rectifier obtained by simple aggregation of three single-phase rectifiers with zone-phase control. It has been established that the level of higher harmonics of currents during the improvement of a three-phase rectifier operating on an active load with large delays in the opening angles of the PSD can be reduced up to 1.7 times.

A new direction for improving controlled rectifiers has been determined, which consists in using combinations of interphase voltage systems. For this, the center of rotation of the multiphase system of windings-vectors with different levels of line voltages is set on the topographic potential plane. The combination of the obtained levels of line voltages expands the operating range of the delays of the opening angles of the PSD to values \( \alpha \in (60^\circ \ldots 180^\circ) \) and improves the shape of the rectified voltages and currents curve.

The boundaries of the ranges of the opening delays of the PSD rectifiers with zone-phase regulation and a coupled three-phase voltage system are established, and analytical expressions are obtained to determine the average rectified voltages for all ranges of the senior and low regulation zones.

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