Research of the three-phase rectifier with a fractional number of zones

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Abstract. In the work simple provisions of the structural synthesis method are used to create new controlled three-phase AC rectifiers with a fractional number of zones. The capabilities of the method are demonstrated by the example of obtaining a simple three-phase two-zone rectifier. The analysis of operating modes indicates the achievement of high energy performance.

1. Introduction

It is known that a smooth change in the controlled rectifier output voltage \( U_d \) is carried out by introducing an artificial opening delay (\( \alpha \)) or control angle for controlled power semiconductors (SPD). By adopting idealized conditions [1], the angle \( \alpha \), in regulation range \( 0 \leq \alpha \leq 180 \), allows one to smoothly change the value (in case of the standard single-phase full-wave rectifier) of:

\[
U_d = \frac{1}{\pi} \int_0^{\pi} u_d \, d\theta = \frac{2\sqrt{2}}{\pi} U_i \cos \left( \frac{\alpha}{2} \right). \tag{1}
\]

However, simultaneously with the angle \( \alpha \), the value of the power factor \( PF \) changes too[2]. And for such circuit in the most rational case, if there is a circuit in the form of a zero (or inverse) diode for an inductively flowing current:

\[
PF = \frac{\sqrt{3}(1+\cos(\alpha))}{\sqrt{\pi}(\pi-\alpha)}. \tag{2}
\]

Dependence (2) clearly shows that \( PF \) will be especially low at the beginning of the regulation range when \( \alpha \to \pi \). The creation of zone-phase control principle, combining some of phase control and amplitude control advantages, caused by the desire to improve the energy indicators of controlled rectifiers [3]. Due to this principle, the \( PF \) value can be increased several times at the beginning of the regulation range.

In general, compared with a standard controlled rectifier, the value of the \( PF \) for zone-phase rectifier increases, on average, by 30-50% dependence on the working areas number taking into account the entire control range \( U_d \) [4].

A further increase of the \( PF \) value is complicated by the fact that a single-phase AC system initially worse than a three-phase AC system in energy indicators value.

Formal analysis conducted for bridge circuits of controlled rectifiers [5] shows the difference in input power factors in the case of the inductive nature of the load, even for an energy-efficient mode, when \( \alpha \to 0 \):

a) for single-phase AC rectifier:
\[
PF = \frac{2\sqrt{2}}{\pi} \approx 0.9; \quad \text{(3)}
\]

b) for a three-phase AC rectifier:
\[
PF = \frac{3}{\pi} \approx 0.955. \quad \text{(4)}
\]

Thus, these examples make it clear that the choice of rational factors can improve the energy performance of controlled rectifiers and, when they are created, preference should be given to three-phase rectification circuits.

The paper aims to take into account the most significant rational factors and obtain a schematic solution of a rectifier with zone-phase regulation and a high \( PF \), which has a minimum installed transformer power, by the means of structural synthesis method.

2. Construction of a three-phase zone-phase rectifier with a fractural number of phases

It is known that the number of primary phases of rectifier transformers is determined by their existing set in the industrial network, i.e. equal to one, two or three phases. In this case, the number of secondary phases obtained on the basis of three initial phases can be expanded by the combination of the transformer secondary phase windings voltages.

For the most advanced bridge rectifiers \[6\], the total power of the multiphase transformer secondary windings \( S'2 \) in relative units with the number of symmetric single-winding secondary phases \( m_2 \):
\[
S'2 = \frac{\pi}{\sqrt{2}} \sqrt{m_2 \sin \frac{\pi}{m_2}}. \quad \text{(5)}
\]

This dependence is presented \( S'2(m_2) \) in the form of Figure 1, where the number of phases \( m_2 \) is conventionally taken as a continuous variable.

![Figure 1. Minimization \( S'2 \) of the phases number \( m_2 \).](image)

The known prevalence of the transformer secondary windings \( S'2 \) total power in the typical power of a transformer is compared to the total power of its primary windings; thus it is necessary to take the optimal phases number \( m_2 \), taking into account the discretization equal to three.

Therefore, if it is technically possible to minimize the typical power of a transformer, the preference should be given to three-phase AC controlled rectifiers with a system of symmetrical secondary phases, the windings of which lie on the transformer rods of the same name \[7\].

A topological method \[8\] is known for the rectifier circuits synthesis. In that method, each resulting rectifying voltage of secondary windings is considered as the maximum possible potential difference on a topographic potential plane. This plane contains the vector diagrams of the existing voltage levels systems that are developed and rotate in time, joined by the SPD.

Thus, the rectifier circuit solutions structural synthesis is based on the use of the electrical circuits geometrical configuration in the form of topological graphs containing secondary windings, combined by equivalent nodes using SPD.
Considering the already proven advantage of a three-phase symmetric system over any other, in case of rectifier with zone-phase regulation building by means of structural synthesis, the voltage level system, which is traditionally represented on a potential plane as a three-beam star, should be taken as the basis.

To organize the principle of zone regulation, each ray of a star can be divided into several zones. When the vector diagram is naturally rotated on the topographic potential plane, separate projections of the three-beam star zones will periodically form maximum values. The number of their combinations in the form of maximum potential differences between the origins and the ends of the vectors of individual zones, which belong to all the stars and form the resulting voltages, will exceed the number of zones themselves.

This is explained by the fact that a three-phase system of vectors divided into separate zones, the projections of which have reached maximum values, has a greater number of combinations than a similar single-phase system. Therefore, it is possible to obtain not only the linear voltage between adjacent phases of the first zone, the second zone, but also the potential difference between the point of one phase of the first zone relative to the point of another phase of the second zone, etc.

Thus, for a three-phase voltage system, it becomes possible to create a controlled zone-phase rectifier with a fractional number of phases.

The communication of different zones areas for each phase can be accomplished by switching controllable SPD, directing the constant in sign potential difference to the load.

After solving the problem of the resulting voltages for each zone methods forming, during the topological analysis of vector diagrams, the final step will be the connection of a three-beam star with two SCR thyristors connected in different directions. Thus, sign-constant projections of voltage systems in the form of potential differences for all phases will be constructed, and a simple three-phase zone-phase rectifier circuit will be obtained (Figure 2).

![Figure 2. The electrical circuit of the three-phase zone-phase rectifier.](image)

3. Results and Discussion

The power factor $PF$ as the main energy indicator of this rectifier will be determined by many factors: the working area number, the delay angle $\alpha$ value, the load nature, transformer parameters, etc. To the greatest extent, ceteris paribus, the $PF$ value depends on the mode of operation, which is determined by the number of the working area and $\alpha$ value [9].

Therefore, the $PF$ values in different operating modes of a zone-phase rectifier with a fractional number of zones with a typical value of a conventional three-phase bridge rectifier comparison are of practical interest.

The comparison of obtained limits in a changes range with the known limits of a single-phase zone rectifier [10] indicates the fractional zone-phase control principle applying effectiveness to create controlled three-phase rectifiers.
Figure 3 represents the following waveforms: \(a, b, c\) – rectified voltage and winding currents of one phase, respectively, for the active and inductive rectifier loads (rectifier is operated in the first zone); \(d, e, f\) – the rectified voltage and currents of the winding of one phase, respectively, for the active and inductive rectifier loads (rectifier is operated in the fractional zone \(\frac{1}{2}\)); \(g, h, i\) – rectified voltage and winding currents for one phase, respectively, for the active and inductive rectifier loads (rectifier is operated in the second zone).

![Waveform Diagram](image)

**Figure 3.** Oscillograms of a three-phase zone-phase rectifier with a fractional number of zones currents and voltages.

In conclusion, it should be noted that the principle of circuit solutions obtaining, shown in this work, has no fundamental restrictions and allows you to build zone-phase rectifiers with any number of zones. The resulting large number of fractional zones will significantly improve the smoothness of the rectifier transition mode from one zone to another.

Thus, in the process of \(U_d\) volume regulation, during the process of SPD control algorithms building, the possibility of switching to an intermediate fractional zone should be taken into account. This will allow the rectifier to operate at lower \(\alpha\) values, which generally contributes to its \(PF\) value increasing and rectified voltage curve shape smoothing.

4. Conclusion

In this paper the capabilities of the structural synthesis method is demonstrated, and schematic solution for a three-phase zone-phase rectifier with a minimum value of the installed winding power equal to \(\pi/3\) is obtained.

The advantages of zone-phase rectifiers operation in a three-phase network, which are expressed in increasing the power factor from 0.9 to 0.955 and using intermediate fractional zones possibility, improving the smoothness of the transition between adjacent zones is shown.

The efficiency of the obtained three-phase zone-phase rectifier was confirmed by means of simulation, and the currents and voltages oscillograms at the rectifier input and output were obtained.
Waveform analysis allows concluding that zones number increasing improves the network currents harmonic composition and the fractional zones with presence of alternative control ranges will optimize the rectifier operation mode and may be the subject of a separate research.

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