Zone phase rectifier with 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. Calculated expressions setting the relationship between the medium-straightened voltage and the value of the SPD opening angle delay for different zones are obtained. The possibility of rectified voltage smooth regulation relative to the current value of the phase winding voltage is shown: in the first zone from 0 to 2.34, in the intermediate fractional zone from 2.34 to 3.7, in the second zone from 3.7 to 4.68. Due to the intermediate fractional zone, partial overlaps in the specified voltage ranges are allowed.

1. Introduction

A topological method [1] is known for the rectifier circuit 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 structural synthesis of the rectifier circuit solutions is based on the use of the electrical circuit 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 the 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 [2].

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 [3]. 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 [4].

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.

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

Firstly it is necessary to mark the location of zones I, II, etc. on the topographic potential plane (Fig. 1).

![Figure 1](image-url)

*Figure 1.* The sequence of a three-phase zone-phase rectifier construction and the zones location (I - first, II - second, III - third, etc.) on the topographic potential plane

The next step is to place in the center a three-phase symmetric system in the form of a three-beam star, each beam of which will be divided by zone boundaries into several parts. To simplify the problem, we must take the condition of first two zones constructing and defining the combinations of potential differences between the beginnings and the ends of the vectors of the individual zones that are in this case [5].

Thus, two working zones with a system of linear three-phase voltages were obtained (Fig. 2): for the first zone $U_{ab1}, U_{bc1}, U_{ca1}$; for the second zone $U_{ab2}, U_{bc2}, U_{ca2}$. Their values, as long as the numbers of turns for all secondary windings parts took equal, will differ by half: $U_2 = 2U_1$, where $U_1$ and $U_2$ are the modules of the first and second zones linear voltages, respectively.

In addition, there are two systems of three-phase voltages, formed by combinations of potential differences between the windings outputs of different phases of the first and second zones. That it how three-phase voltage systems $U_{ab12}, U_{bc12}, U_{ca12}$ are formed, between the first and second zones and $U_{ab21}, U_{bc21}, U_{ca21}$, between the second and first zones with the same line voltage modules, which are 1.57 times higher than the voltage $U_1$. 
Figure 2. Formation of the combinations of secondary windings potential differences: a - the first zone linear voltages; b - the second zone linear voltage; c - voltage combinations between the first and second zones; d - voltage combinations between the second and first zones.

The presence of SPD links with the rays of all parts of the stars should ensure that the star beam, which has a decreasing projection on the axis of the resulting voltage, can naturally disconnect the SPD, and instead, the next beam switches on with a 120° delay. This condition is satisfied for systems of linear three-phase voltages $U_1$ and $U_2$.

However, an analysis of voltage combinations between the first and second zones $U_{12}$ (Fig. 2, c) and between the second and first zones (Fig. 2, d) shows the inevitable intersection of the vectors ($U_{ab12}$, $U_{bc12}$ and $U_{ca12}$, $U_{ab21}$, $U_{bc21}$ and $U_{ca21}$). In practice, this will lead to the imposition and overlapping of conductive circuits, which will complicate the switching process of controlled SPD and make it difficult to close them in case of circuits with SCR thyristors [6]. The idealized process fragment of such switching is shown in figure 3. It can be seen that the rotation of the vector diagram with speed $w$ leads to a decrease in the voltage projection $U_{12}$ and the SPD connected to the nodes $C_2$ and $B_{12}$ should close naturally, and to replace them the SPD connected to the nodes $B_2$ and $C_{12}$ should be opened for use by the voltage rectifier, the projection of which increases at this time.

However, at the time of switching, all SPDs connected to the marked nodes in figure 3 will be open. This will lead to the imposition of conductive circuits and the subsequent closure of the SPD connected to the node $C_2$ in a natural way will be impossible, since the current flow contour will open due to the potential difference between the nodes $B_2$ and $C_2$. This current will keep the thyristor connected as controlled SPD to the node $C_2$ in the open state.
Figure 3. The process of the switching of two voltage systems

So the rectifier spontaneously switches to the operation mode in the second zone with line voltages $U_2$.

Therefore, if there is no task to complicate the circuit design of a three-phase zone-phase rectifier, then when building control algorithms for SCR thyristors (as SPD), turning the topographic potential plane of the vector diagrams, it is enough to exclude the joint participation of voltage systems $U_{12}$ and $U_{21}$ in the formation of their projections on the resulting voltage axis [7].

As a result, the rectifier will be able to work separately with the voltage system, $U_{12}$ or $U_{21}$, remaining on the intermediate fractional zone. The location of the voltage vectors (Fig. 3, c and Fig. 3, d) and their alternation in this zone allows one-way direction of the rectified current with respect to the nodes of the three-pointed star. This forms a rectified voltage in which the linear voltages of the first zone $U_{21}$, with six pulsations, alternate with combinations of system voltages $U_{12}$ or $U_{21}$.

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 [8]. 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 (Fig. 4).

Figure 4. The electrical circuit of the three-phase zone-phase rectifier

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 [9,10].

Therefore, it is of practical interest to the $PF$ values at 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 is of biggest practical interest.

The obtained changes range limits comparison with the known limits of a single-phase zone rectifier [6], indicates the fractional zone-phase control principle, applying effectiveness to create controlled three-phase rectifiers.

Figure 5 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 for one phase, respectively, for the active and inductive rectifier loads (rectifier is operated in the fractional zone 1,5); $g$, $h$, $i$ - rectified voltage and winding currents for one phase, respectively, for the active and inductive rectifier loads (rectifier is operated in the second zone).

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 building SPD control algorithms, 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.

**Conclusion**

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, are shown.

In this paper the capabilities of the structural synthesis method are 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.

Calculated expressions, setting the relationship between the medium-straightened voltage and the value of the SPD opening angle delay for different zones, are obtained. The possibility of rectified voltage smooth regulation relative to the current value of the phase winding voltage is shown: in the first zone - from 0 to 2.34, in the intermediate fractional zone - from 2.34 to 3.7, in the second zone - from 3.7 to 4.68. Due to the intermediate fractional zone, partial overlaps in the specified voltage ranges are allowed.

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