Power performance single-phase rectifier depending on topology and control methods

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***Abstract* — The article introduces simple regulations of simple method specifications, based on structural synthesis method, for controlled rectifiers of the single-phase alternating current development. It is proved that the structural synthesis method is useful in improvement of zone rectifiers' circuits and in increasing of their power indicators. It was found that the phase control method of output voltage regulation leads to the low input power factor for a single-phase zone rectifier. In this accordance the sector control method was offered for the first regulation zone.**

***Keywords* — method, structural synthesis, sector control, energy performance, rectifier.**

I. INTRODUCTION

Energy performance of static electric power converter is defined not only by the parameters of the applied elements but it is mostly dependent on its circuit design solution. This was illustrative of setting up and improving the alternating current rectifiers, for which increasing values of power factor (χ) and efficiency factor (η) were always taken into consideration within the practical context. In this case, the circuits of common rectifiers are developed by using the heuristic method [1].

The application of structural synthesis in case of circuit analysis for static converters is always associated with certain difficulties. Static converters contain elements with nonlinear volt-ampere characteristics and allow a huge number of alternative options combinations of fixed relationships (topological structures) between the individual elements (for example, power semiconductor devices – PSD).

There are a lot of circuit design solutions of rectifiers based on semiconductors with passable power characteristics for three-phase alternating current rectification. But in case of one-phase alternating current, there are not enough suitable rectifying circuits [2].

II. PROBLEM STATEMENT AND THEORY

The article sets the objective to disseminate methods of structural synthesis for controlled rectifiers current, to show ways of improving searching principle and to evaluate the impact of topological structures compounds of PSD and control methods on power characteristics.

A single-phase alternating current rectifier with development of circuit design of high power indicators is complicated by the fact that a single-phase alternating current system is originally has worst energy indicators than those of the three-phase alternating current system.

The formal analysis shows that the three-phase rectifier enables one to provide the input power factor for inductive nature of load, approximately:

$$\chi = 3/\pi \approx 0.955. \quad (1)$$

At the same time, the single-phase alternating current rectifier provides:

$$\chi = (2\cdot\sqrt{2})/\pi \approx 0.9. \quad (2)$$

In addition, value χ of operating rectifier appears to be much dependent on the value of artificial delay α. This artificial delay in the opening PSD implements the principle of phase control and possibility of regulation of the rectified voltage value (U_d). However, there is a significant drawback in this principle, consisting in extremely low values of the χ controlled rectifiers in the range of low voltages U_d [3].

This drawback is eliminated in so called zone-phase alternating current rectifiers [5]. The zone-phase regulation is a voltage regulation where the switching sections of the secondary winding transformers and variation of semiconductors opening angle are used simultaneously.

The bridge-circuit rectifier of four-zone single-phase alternating current is most common. An advantage of zone-phase regulation is a clear example of dependence χ (α) or similar dependence χ (U_d) as $U_d = U_{d\ max} \cdot \cos(\alpha)$. Figure 1 shows dependences χ (U_d) for two single-phase alternating current rectifiers: with phase regulation (Curve 1) and four-zone regulation (Curve 2). I, II, III and IV show the power factor value of the four-zone rectifier in dependence of a zone number. Curve 1 is above curve 2 on average by 35-40%.

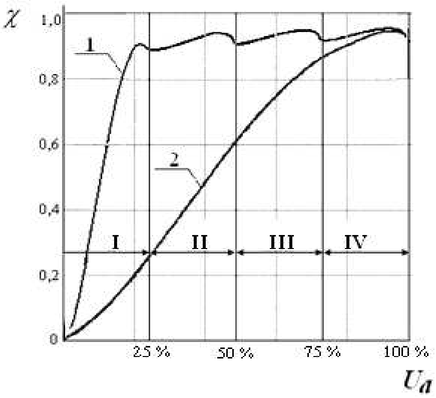

Fig.1. Dependence of power factor of controlled single-phase rectifiers on rectified voltage value

However, it is well-known that zone-phase rectifiers have their own disadvantages (great quantity of PSD cascade connection in the chain of rectified current, sneak circuits of overlapping (commutation) and etc.) which do not allow values χ and η to reach their own theoretical maximum [6], decreasing, in practice, these performance indicators by 10 – 15%.

For this purpose, it is necessary to develop efficient synthesis methods of single-phase alternating current rectifiers which will allow to search rational circuit design solutions without these disadvantages.

III. Application features of structural synthesis method for controlled single-phase alternating current rectifiers

Formalization and extension of this method for single-phase alternating current rectifiers operating are connected with generally accepted assumptions of elements' ideality used in rectifier setting up: commutation takes place instantly and without losses; transformer windings have no resistance and leakage inductance, and so forth.

Each resulted rectified voltage should be considered as maximum electric potential difference on the topographic potential plane with time base sweep of voltage, represented in the form of a vector diagram with relation to structural synthesis [5]. For synthesis convenience, it is also accepted that the magnitude of the voltage vector corresponds to their secondary winding of transformer and reflects their peak value. It is appropriate to consider the examples of method and more simple application of its specifications.

The authors represent the rotating secondary winding vector on the topographic potential plane and take into account the fact that each of the winding leads forms both a positive and negative potential at different times (Fig. 2, a). To achieve one-side conduction in every operating period, it is required to attach semiconductors, included in different direction, to each winding terminal on a given plane (Fig.2, b). In this case, the free contacts of semiconductors on the topographic potential plane form a significantly constant polarity from the practical point of view. Thus, it is possible to obtain a rectification scheme (Fig. 3), known as the single-phase Grets-Pollack bridge circuit [2].

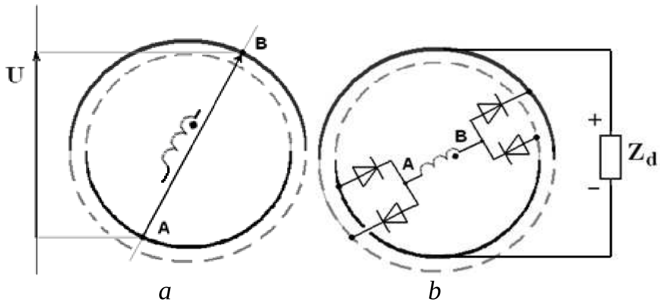

Fig.2. Synthesis of single-phase alternating current rectifier: a - representation of the projection of the potential difference of the winding leads at an arbitrary time; b – obtaining a constant-sign potential difference

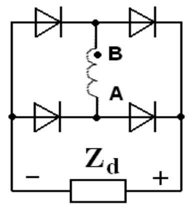

Fig.3. Single-phase bridge rectifier

An uncontrollable bridge rectifier can be transformed by replacing diodes, controlled by PSD on thyristors, into the controlled bridge rectifier of single-phase alternating current with phase regulation. Applying opening signals to PSD with the delayed-action at angle α, there is an opportunity to observe a picture of accessible potentials (Fig.4). Diagonal maximum difference projection will give a typical oscillogram of voltage output (or current, in case of active load), the half-period average value of which is regulated by changing the α value.

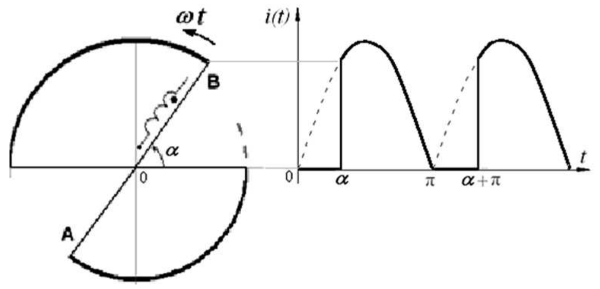

Fig.4. Wave output current production diagram of controlled rectifier with phase control

IV. EFFICIENCY UPGRADING OF SINGLE-PHASE ALTERNATING CURRENT ZONE-PHASE RECTIFIERS BY THE STRUCTURAL SYNTHESIS METHOD

To build simple zone-phase rectifier, it is enough to combine several bridge rectifiers and to use a combination of both amplitude and phase methods of output voltage regulation.

A two stage single-phase rectifier was produced by using aggregation as the most common approach in the structural synthesis method (Fig. 5). This is the result of the combination (aggregating) of already known circuits.

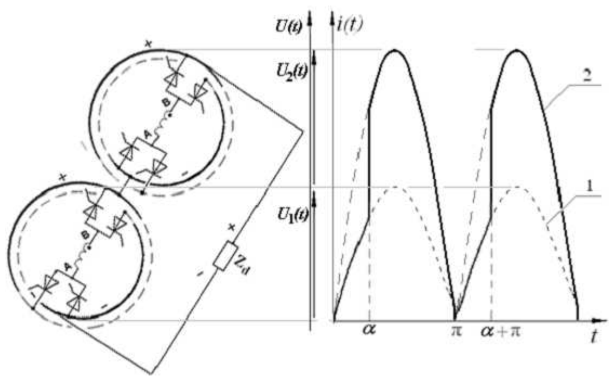

Fig.5. Synthesis of a two-zone rectifier by aggregation - combination of two single-phase alternating current bridge-circuit rectifiers and construction of wave diagrams

Curves in Figure 5 demonstrate availability of active load: 1 – first step (zone/stage) and 2 – second step (zone/stage) of rectified voltage (or current). The schematic circuit diagram can be produced in dual zone execution (Fig.6) and, in practice, it is known as the Ogier circuit [7].

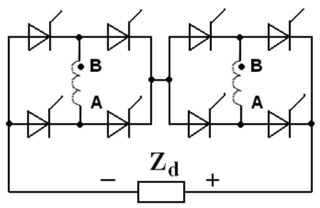

Fig.6. Schematic diagram of Ogier scheme

A simple analysis demonstrates that such circuit has a double number of PSD, which are step-by-step connected on the way rectified current flows. Such type of connection doubles the capacity losses, decreases η value and restricts practical application. To decrease capacity losses, a number of PSD, connected on the way of rectified current, needs to be reduced. Such zones combination (merging) feasible, for example, through their combination (Fig. 7,a).

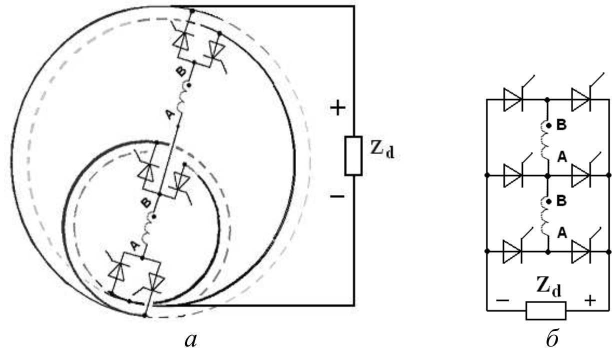

Fig.7. Synthesis of a two-zone rectifier by merging (absorption): production of two zones by locus potential distribution of rotating windings-vectors – a; basic scheme of bridge zone-phase rectifier – b

Due to such combination (merging), half of PSD can be significantly reduced. The reduction will entail increasing of η value and value of reduced capacity losses in PSD (in practice η is increased at an average of 3 – 5 %). The rectifier at Figure 7,b is widely spread and known as bridge zone-phase rectifier [5].

It has an acceptable value of η ≥ 0.95, but another energy index, represented graphically by the dependence χ(α). It reaches its maximum (χ ≈ 0.9) in only a few points, even theoretically. In practice, this indicator is not high enough, especially in the first regulation zone, where the power factor is χ ϵ 0…0.82. To increase the energy indicators, the factors on which it depends need to be identifyed.

V. ZONE-PHASE RECTIFIERS ENERGY EFFICIENCY INCREASING BY DEVELOPING METHODS OF SEMICONDUCTOR CONTROL

Calculation expression of power factor χ:

$$\chi = P / \sqrt{(P^2 + Q^2 + T^2)} = K_s \cdot K_d, \quad (3)$$

where P, Q and T – active power, reactive power and the power of distortion correspondingly, K_s – shift coefficient, K_d – distortion coefficient.

The value of K_d is determined by high harmonic of grid current, which is the reason why expression $K_d < 1$, in case of the controlled rectifier of those semiconductors used like switches, is almost always true. The value of K_s is determined by the shift angle between the main harmonic of grid current and the main harmonic of grid voltage $K_s = cos(\varphi)$. In case of the controlled rectifier, this shift ensured by the thermistor's opening delay in the process of phase regulation.

The main harmonic of grid current shift should be compensated to increase the value of the power factor in the first regulation zone because the delay of semiconductor`s opening can not be denied. This compensation theoretically could lead the value of K_s to 1. In this way, rational control methods using is one of the effective ways to improve energy indicators of zone-phase rectifiers [2].

The principle of current`s main harmonic shift, which is built on SCR-thyristors, is known as sector regulation. To carry out forced closing of SCR-thyristors, locking circuit need to provided, but it is economically inefficient. But due to semiconductors, developing the new elemental base can be offered.

In that case, smooth regulation of output voltage can be achieved by simultaneous shift of leading (α) and back (β) edges of main harmonic of grid current (Fig.8). Such regulation method does not incur phase shift (φ).

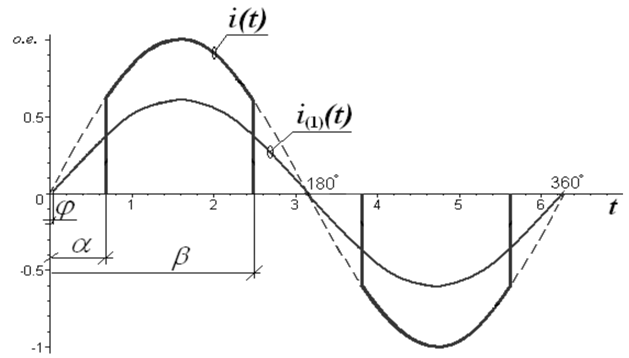

Fig.8. Grid current curve and fist harmonic of rectifier output current in case of sector regulation

If rectifier is accepted as active load, then, for the phase control method, one can define K_s as:

$$K_s = I^{sin}_{(1)} / \sqrt{(I^{sin}_{(1)})^2 + (I^{cos}_{(1)})^2}, \quad (4)$$

where, $I^{sin}_{(1)}$ - sine rectifier current curve component, $I^{cos}_{(1)}$ - cosine rectifier current curve component. Expressing the grid current curve as $I_m\ sin(wt)$ in the range from α to π, it turns out that $I^{sin}_{(1)} = (I_m / \pi) \cdot (\pi - \alpha + 0.5 \cdot sin(2\alpha))$, and $I^{cos}_{(1)} = (I_m / \pi) \cdot (- sin(\alpha))$.

Hence:

$$K_s = \pi - \alpha + 0.5 \cdot sin(2\alpha) / \sqrt{sin^4(\alpha) + (\pi - \alpha + 0.5 \cdot sin(2\alpha))^2}. \quad (5)$$

The distortion coefficient expression is:

$$K_d = I_{(1)} / I = \sqrt{(I^{sin}_{(1)})^2 + (I^{cos}_{(1)})^2} / \sqrt{2} \cdot I, \quad (6)$$

where, I- the effective value of rectifier grid current, $I_{(1)}$ – the effective value of rectifier main current harmonic.

Hence:

$$K_d = \sqrt{sin^4(\alpha) + (\pi - \alpha + 0.5 \cdot sin(2\alpha))^2} / \sqrt{\pi \cdot (\pi - \alpha + 0.5 \cdot sin(2\alpha))}. \quad (7)$$

Therefore, the power factor of the rectifier only with active load is defined as:

$$\chi = K_s \cdot K_d = \sqrt{(\pi - \alpha + 0.5 \cdot sin(2\alpha) / \pi)}. \quad (8)$$

If the rectifier operates inductive load then shift coefficient dependence is:

$$K_s = \sqrt{(1 + cos(\alpha)/2)}. \quad (9)$$

and distortion coefficient:

$$K_d = 2 \cdot \sqrt{1 + cos(\alpha)} / \sqrt{\pi} \cdot \sqrt{(\pi - \alpha)}. \quad (10)$$

Shift coefficient of the rectifier with inductive load in case of sector regulation method:

$$K_s = cos(\beta) - cos(\alpha) / \sqrt{(cos(\beta) - cos(\alpha))^2 + (sin(\beta) - sin(\alpha))^2}. \quad (11)$$

The distortion coefficient of the rectifier with inductive load in case of the sector regulation method:

$$K_d = (\sqrt{2/\pi}) \cdot \sqrt{(cos(\beta) - cos(\alpha))^2 + (sin(\beta) - sin(\alpha))^2 / \beta - \alpha}. \quad (12)$$

The power factor of the rectifier with inductive load in case of the sector regulation method:

$$\chi = (\sqrt{2/\pi}) \cdot (cos(\beta) - cos(\alpha)) / \sqrt{(\beta - \alpha)}. \quad (13)$$

For the sector regulation principle, $\beta \approx \pi - \alpha$, where $cos(\beta) = - cos(\alpha)$, $sin(\beta) = sin(\alpha)$ are an expression for defining power indicators. Table 1 contains expressions to define power indicators for the first regulation zone.

TABLE I. THE ENERGY PARAMETERS OF THE RECTIFIER IN THE FIRST CONTROL ZONE IN THE CASE OF VARIOUS PRINCIPLES OF CONTROL OF THE CSE

Index	**Principles of control**	
	Phase control	***Sector control***
K_s	$\sqrt{(1+cos(\alpha)/2)}$	1
K_d	$2\sqrt{(1+cos(\alpha)}/\sqrt{\pi} \cdot \sqrt{(\pi-\alpha)}$	$2\sqrt{2cos(\alpha)}/\sqrt{\pi} \cdot \sqrt{(\pi-2\alpha)}$
χ	$\sqrt{2(1+cos(\alpha)}/\sqrt{\pi} \cdot \sqrt{(\pi-\alpha)}$	$2\sqrt{2cos(\alpha)}/\sqrt{\pi} \cdot \sqrt{(\pi-2\alpha)}$

According to fig. 9, it can be seen that the sector control method on the first regulation zone is much more effective than the phase control method. Values of curve 2 in fig.9 are above curve 1 by an average of 22% over the entire control range. This fact contributes to the extra increase in the power factor value of the zone-phase rectifier.

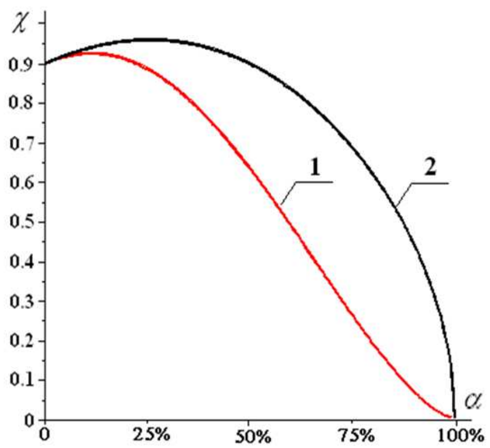

Fig.9. Differences in the power factor of a ladder-type rectifier: phase regulation – 1 and sector regulation – 2 on the first zone

VI. Conclusions

It was found that the phase control method of output voltage regulation leads to a low input power factor for a single-phase zone rectifier. And that is the reason why it should be replaced by the sector control method which power factor is 35-40% higher.

It was shown that structural synthesis of the controlled rectifiers method allows one to conduct a directed search for rational circuit solutions, providing high energy performance, determined by the efficiency and power factor.

The authors proved that the choice of the rational control method for semiconductors allows one to increase the power factor by an average of 22%.

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