Zone rectifier as facility of increasing energy efficiency of DC drive

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Abstract. This paper introduces prospects for further development of a single zone-phase rectifier aimed to research and improve it. The improvement of circuitry these zone-phase control circuits makes it possible to decrease the number of power semiconductors, to decrease commutation losses, to increase power factor, and finally, to increase efficiency. A new radial type circuit and its advantages are provided as well. The analysis results of zone-phase regulator circuit shows that the ways of improving their energy performance are oriented towards the development and improvement of new circuit design rectifiers and control principles.

1. Introduction
The control of traction motor’s rotation speed on electric locomotive, electrified with one-phase alternating current, is achieved by changing the value of current and voltage. It becomes possible through the use of amplitude regulation. This type of regulation is based on the principle of changing secondary winding commutation combinations by contactors. The main disadvantage of amplitude regulation is impetuous steps of output voltage value which cause the scorching of contacts. The intention to provide a smooth voltage change led to phase regulation method creation. This method is based on the delay of thyristor unlocking principle acting as electronic switch and the value of average rectified voltage depends on the conducting state duration. But the major disadvantage of this principle is the great reactive power creation due to phase control, that generally reduces the energy indicator rectifiers. All stated minuses are mostly eliminated in so-called zone or zone-phase regulators. This type of regulation is a way of combination of voltage control on the traction-feeding transformer windings of AC electric motive power whereby the switching sections of the secondary winding transformers and variation of silicon-controlled rectifier (CSR) opening angle are simultaneously applied. Different options of zone-phase voltage regulation are applied and they differ by the number of zones and voltage ratios. Nowadays four-zone regulators built on thyristor bridge rectifying circuit are getting widespread use [2].

Electric lokomotives with one-phase bridge AC rectifier in contrast to others have a gradual acceleration in a traction mode but they have sub-optimal value of energy indicators, especially power factor. In typical operation of these electric locomotives the rectifier power factor does not exceed 0.8. This phenomenon is explained by the forced delay action of the used four-phase converter connection with bridge gate having two commutation circuits simultaneously (small and big) resulting in the energy hub shift of the rectified voltage towards current in input and output circuits.
The low power factor value shows that there are high reactive power consumption and power current form distortion. In this case electric-traction network and electromotive electrical equipment are loaded by auxiliary reactive current resulting in the increased energy consumption to hauling operations.

2. Methods and tools of power factor increase

To compare methods and tools aimed at improving the zone rectifier energy indicator the factors depending on the power factor should be assessed:

\[
\chi = \frac{P}{\sqrt{(P^2 + Q^2 + T^2)}} = K_m \cdot K_d
\]

where \(P\), \(Q\) and \(T\) – active, reactive power and the power of distortion correspondingly, \(K_m\) – shift coefficient, \(K_d\) – distortion coefficient.

The double commutation circuit problem was eliminated in an improved version of the four-zone rectifier with a ladder structure (Fig. 1) and a new simpler algorithm of thyristor control.[1]

![Figure 1. The power part of the four-zone rectifier with the ladder structure scheme](image)

Owing to special circuit design topology the general commutation process duration is reduced by half in the rectifier for the majority of operation zones. This allows one to increase the power factor by 4-5%. In addition, the decrease of switching angle \(\gamma\) decreases capacity and dimensions of static reactive power compensator equivalently in case of their application for AC electric locomotives.

One of the efficient sorting out the problem and energy efficiency upgrading of AC electric freight locomotives is the zone rectifier control algorithm improvement [3].

As one cannot refuse of opening delay rectifier invention towards the value of firing delay angle in zone rectifiers then for increasing power factor value in the first zone it is neccessary to compensate the shift of fundamental component of line current caused by the delay.

This compensation principle is known as a sector controlling. For common SCR-semiconductor switches the forced commutation is conjugated with the introduction of switch locking circuits and it is not cost-effective. However the sector controlling principle could be passed on a new element base with the advancement of power semiconductors.

In this case, the control of the traction motor in the first zone will be effected with simultaneous offset for angle \(\alpha\) of the leading edge and with the same offset for angle \(\beta\) but in the opposite direction of rear current front ensure that any phase displacement \(\phi\) of the main harmonics of line current would not be caused (Fig. 2) [2].

Theoretically, sector regulation increases the average power factor by 25-30%, given that electric locomotives run utmost using the 1-st zone.
Sector controlling principle improves the transformation of energy efficiency by means of reactive power compensation, optimizing $K_m \leq 1.0$.

Figure 2. The network current curve and its first harmonic rectifier in case of sector regulation

3. Ways of zone converter efficiency increasing

Efficiency is defined by the active power ratio in the output of transformer to active power in its input. Applied to rectifying performance of zone-phase converter this means [4]:

$$\eta = P_d / P_t = P_d / (P_d + \Delta P_{\text{lost}}),$$

where $\Delta P_{\text{lost}}$ is losses of active power in zone-phase converter.

These losses are the sum of the losses in transformer and losses in rectifier elements—thyristors and diodes:

$$\Delta P_{\text{lost}} = \Delta P_{\text{tr}} + \Delta P_{\text{th}} + \Delta P_{\text{dio}}.$$  \hspace{2cm} (3)

According to this arguments we could say that efficiency of converter increases through decreasing sum of thyristor and diode losses $\Delta P_{\text{th}} + \Delta P_{\text{dio}}$. In other words efficiency increases owing to decreasing number of thyristors and diodes through which current is passed at the same time.

Let us compare the equivalent circuits of bridge and ladder converters (Fig.3 and Fig.4) in their second zone of regulation. Four power semiconductors are involved in the bridge converter, and three power semiconductors are involved in the ladder converter.

Figure 3. The equivalent circuit of bridge rectifier converter for the second regulation zone

Thus it is possible to increase the efficiency of converter by decreasing power semiconductor losses by 25%.

The further improvement of topology circuit with zone-phase control will provide a decrease of the number of power semiconductors both in the circuit as a whole and the number of devices where current flows simultaneously through the circuit in each control zone and will have a higher power factor and less commutation losses. Taking into account these advantages, the zone-phase circuit development is expedient in practice.
Figure 4. The equivalent circuit of the ladder rectifier converter for the second regulation zone

4. Conclusion
The analysis results of zone-phase regulator circuit shows that the ways of improving their energy performance are oriented towards the development and improvement of new circuit design rectifiers and control principles.

Rectifiers with the ladder structure have a less switching processes period compared to the bridge rectifier. The ladder structure rectifier application as the element of the AC electric locomotives traction converters allows one to improve the energy performance and first of all power factor by an average 2-4%. Theoretically, sector regulation increases the average power factor by 25-30%, given that electric locomotives run utmost using the 1-st zone.

The further improvement of these zone-phase control circuits makes it possible to decrease the number of power semiconductors, to decrease commutation losses, to increase power factor, and finally, to increase efficiency. Converters with the ladder topology decrease losses in power semiconductors by 25% thus with regard to all pluses, the future progress of zone-phase control circuits is useful for practical application.

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