Pulse-Width Control in Ladder Structure Four-Phase Rectifier for AC-Electromotive

V V Ivanov¹, S V Myatez², E G Langeman³, N I Schurov⁴
¹,²,³,⁴Novosibirsk State Technical University, Novosibirsk, 630073, Russia

E-mail: ivanov.etk@yandex.ru

Abstract. Based on these studies the ways of power factor of the single-phase rectifiers operating in a single-phase AC network improving are suggested. The ladder four-phase rectifier is offered as a technical mean using a pulse-width method of controlling the rectified voltage. The pulse-width control efficiency as a way of the power factor rectifier with a ladder structure for AC electromotive improving is evaluated.

Introduction
Electromotive with the one-phase bridge AC rectifier in contrast to others has a gradual acceleration in a traction mode but also has a not optimal efficiency factors, e.g. power factor. In a normal electromotive’s operation mode its power factor doesn’t exceed the meaning 0.8. This phenomenon is explained by the forced delay in the used four-phase transducer with the bridge rectifier structure with two commutation circuits (small and big) which cause the move of the rectified voltage electrical center along the current in the input and output circuits.

Low power factor value shows that there are high reactive power consumption and supply current form distortion. In this case electric-traction network and electromotive electrical equipment is loaded by the particular reactive current which causes the increased energy consumption while traction mode.

1. Methods of the power factor’s increasing
The factors which influence on the power factor should be evaluated for the problem of power factor increasing in the first rectifying zone:

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

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

As a technical mean of the energy effectiveness factor increasing improved four-zone rectifier with so called semiconductor distortion factorswitch ladder structure [1] was proposed by the authors.

By means of the special scheme solution topology general commutation process duration is reduced by half in the rectifier for the majority of the operation zones. This allows increasing the power factor by 4-5%.

The increasing of the AC working freight electromotive energy effectiveness by the zone rectifier control algorithm improvement is the effective solution [2].
As far as creation of the rectifier opening delay by a firing delay angle in the zone rectifier couldn’t be refused, for the power coefficient value increasing in the first zone the distortion fundamental component compensation should be made.

This principle is known as a sector controlling. For common SCR-semiconductor switches forced commutation is attended with the commutation key out circuits’ injection which is not cost-effective. However power semiconductors perfection allows using the sector controlling principle with new element base.

Sector controlling principle increases the transformation energy efficiency by means of reacting power, so $K_m \leq 1.0$. Sector controlling effect is carefully described in source [3].

For the additional power factor increasing it is necessary to increase distortion factor value. The distortion factor is the ratio of the effective range of the primary winding first current harmonic to the effective range of the primary current.

For reducing the influence of higher harmonic component on the power factor was offered to use the pulse-width controlling of the rectifier first zone voltage.

The pulse-width controlling is a controlling of the average on-load voltage value by means of the pulse duty factor and control key.

The pulse-width controlling is realize as well as the sector controlling with the help of the semiconductors switches substituting with fully controlled power semiconductors.

2. Current curves’ harmonic analysis

It is known, that any periodic function with a finite number of discontinuities of the first kind and a finite number of highs and lows for the period, can be arranged in the trigonometric series (Fourier series):

$$f(\omega t) = A_0 + A_{1m} \sin(\omega t + \phi_1) + A_{2m} \sin(2\omega t + \phi_2) + ... =$$

$$= \sum_{k=0}^{\infty} A_{km} \sin(k\omega t + \phi_k)$$

(2)

where $k = 0 - A_{km} = A_0$; $\phi_k = \phi_0 = \frac{\pi}{2}$.

The first member $A_0$ of the series is called constant component, the second $A_{1m} \sin(\omega t + \phi_1)$ - primary or first harmonic. The remaining members of the series are called higher harmonics.

If the expression (2) discloses the amount of each harmonic of Sines, it takes the form:

$$f(\omega t) = A_0 + B_{1m} \sin \omega t + B_{2m} \sin 2\omega t + ... + B_{km} \sin k\omega t + ... +$$

$$C_{1m} \cos \omega t + C_{2m} \cos 2\omega t + ... + C_{km} \cos k\omega t + ... =$$

(3)

$$= A_0 + \sum_{k=1}^{\infty} B_{km} \sin k\omega t + \sum_{k=1}^{\infty} C_{km} \cos k\omega t$$

where $B_{km} = A_{km} \cos \phi_k$; $C_{km} = A_{km} \sin \phi_k$.

When the $f(\omega t)$ functions number is analytically set, then coefficients can be calculated using the formulae:

$$A_0 = \frac{1}{2\pi} \int_{0}^{\frac{2\pi}{\omega}} f(\omega t) d(\omega t);$$

(4)

$$B_{km} = \frac{1}{\pi} \int_{0}^{\frac{2\pi}{\omega}} f(\omega t) \sin(k\omega t) d(\omega t);$$

(5)
\[ C_{km} = \frac{1}{\pi} \int_0^{2\pi} f(ot) \cos(kot) \, d(ot). \]  (6)

then you can move to the form:

\[ A_{km} = \sqrt{B_{km}^2 + C_{km}^2}; \phi_k = \arctg\left(\frac{C_{km}}{B_{km}}\right). \]  (7)

Distortion factor is defined as the ratio of the effective value of the main harmonics to the current value of the entire function:

\[ K_{nt} = \frac{A_{km}}{A}. \]  (8)

3. **The pulse-width controlling modulation**

The rectifier model was made by the authors in analytical modeling environment MathCad for the current curves’ harmonic analyses while the pulse-width voltage. For the analytical model with pulse-width controlling unipolar signal front sweep was used.

Consider a program for spectral modeling method of regulating the sector:

**Diskretetime setting:**

\[ N = 5000; \quad Q = 0; \]  (9)

\[ d = 2 \cdot \frac{P}{N} \quad n = Q...N; \]  (10)

\[ O_n = n \cdot d. \]  (11)

**Sweep signal:**

\[ r = \frac{-1}{p} \cdot a \tan\left(\sin(A \cdot O_n - \frac{P}{2}) + \frac{1}{2}\right); \]  (12)

**Control signal setting:**

\[ m = 0.8 \sin(O_n); \]  (13)

\[ i_n = \text{if}\ (i_{1n} > 0, i_{1n}, -(i_{1n})). \]  (14)

**Definition of the modulator output signal and converter current:**

\[ m_n = \text{if}\ (i_n < S_n, 100, 0); \]  (15)

\[ i_n = \text{if}\ (n > 2500, -(m_n), m_n). \]  (16)

Picture 1 shows the sweep waveform – r, control signal – m, line current – i(t) and the first harmonic current i_1(t).
Figure 1. The rectifier model with the sector controlling in the first controlling zone

The control signal $m$ amplitude changing causes the fill-factor value $D$ changes, which is defined as:

$$D = \sum_{n} m_n. \quad (17)$$

To determine the range of output current it is necessary to calculate the coefficients of a Fourier series [3]:

$$A_k = d \cdot \left( \sum_{n} i_n \cdot \cos(k \cdot n \cdot d) \right) / \pi \quad (18)$$

$$B_k = d \cdot \left( \sum_{n} i_n \cdot \sin(k \cdot n \cdot d) \right) / \pi \quad (19)$$

$$C_k = \sqrt{A_k^2 + B_k^2}. \quad (20)$$

With help of this model output current spectrum of the rectifier was defined (Fig. 2).

Figure 2. The output current spectrum of the pulse-width controlling rectifier
The result of the harmonic analysis is the dependence of distortion from the fill factor. The comparison of the phase, sectoral and pulse-width voltage regulation methods is presented in Figure 3. The graph shows that the principles of sectoral and pulse-width controlling methods are significantly more effective phase control method. Values of the 2 curve are above the curve 1 22% on average, but the usage of the pulse-width controlling method increases the power factor on the first 10% of the regulation range, changing the duty factor (D) from 0 to 1.

![Figure 3. The differences between the power factor of the ladder structure rectifier 1 – phase controlling 2 – sector controlling 3 - pulse-width controlling on the first zone](image)

4. Conclusion
As the analytical modeling shows by means of the pulse-width controlling principle the rectifier energy indicator increases by 10% on the first controlling range. Authors offer to combine sector and pulse-width methods of the voltage controlling for obtaining better energy indicator.

Reference
[1] S A Evdokimov, L G Evdokimova One-phase AC-DC rectifier, Patent of Russia (2009) 2398344
[2] G S Zinovev Bases of the power electronics Novosibirsk NSTU (2003)
[3] S V Myatezh, N I Schurov, M M Dzhaborov Sector controlling in ladder structure four-phase rectifier for AC-electromotive Elektrotehnik (2014)
[4] A V Plaks, Sistemy upravleniya elektricheskikh podvizhnym sostavom. Ucheb Dlya vuzov zh.-d. transporta Moscow: Marshrut (2005)
[5] B G Yuzhakov Elektricheskii privod i preobrazovateli podvizhnogo sostava Moscow: Uchebno-metodicheskii Tsentro Obrazovaniyuna Zh-d Transporte (2007)
[6] B A Tushkanov, N G Pushkarev and L A Pozdnyakova Rukovodstvo po ekspluatatsii Moscow: Transport (1992)
[7] Yu M Kulinich Elektronnyai preobrazovatel’naya tekhnika: Uchebn posobie Khabarovsk: Far Eastern State Transport Univ (2008)