Influence of load type on power factor and harmonic composition of three-phase rectifier current

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Abstract. This article is devoted to research of the harmonic composition of the three-phase rectifier current consumed when it operates with different types of load. The results are compared with Standard requirements.

1. Introduction
Energy saving is an important state task [1, 10]. The most effective method of saving energy is to provide a power factor equal to one. At the same time, the total power of the power supply source is equal to the active power consumed by the equipment. Absence of reactive power component affects positively the energy efficiency of equipment. For this purpose, it is necessary to use special devices - power factor correctors [2, 3]. Such devices are widely used in single-phase power supplies. However, powerful lighting equipment requires using the three-phase power supplies. Most lighting devices use converters from alternating to direct voltage. To ensure electromagnetic compatibility, international and state standards require the harmonics of current consumption according to GOST R 31751.3.2 [4-6]. The lighting equipment is a technical equipment of C Class, and the relative amplitudes of the higher current harmonics must meet the requirements specified in Table 1.

The simplest circuit of the converter for transforming the alternating to direct voltage is, as a rule, an uncontrolled bridge rectifier, made according to the Larionov scheme [7-9, 15]. Let us consider the Larionov rectifier working in several modes with different types of load and analyse the harmonic composition of the current consumed [20].

2. Operating modes of the Larionov rectifier
There are three modes of operation for the Larionov rectifier, shown in Figure 1: the active load (Figure 1b), the load with constant current stabilization [16] (Figure 1c) and the load with the power consumption stabilization function (Figure 1d).

The harmonic composition of the current consumed depends on the load type. Let us give a calculation, using the active load as an example.

When the load of the three-phase rectifier is active resistance, the shape of current consumed coincides with the shape of the rectified voltage when the phase current value is not zero (Figures 1a and 1b).

The phase RMS current value for this mode is defined as:
The normalized voltage can be obtained from the Fourier series expansion of the current curve and is defined as:

\[
I_d = \sqrt{\frac{2}{\pi}} \int_{0}^{\frac{\pi}{6}} \sin(t) \cdot \sin\left(t + \frac{\pi}{6}\right) \cdot dt = \frac{2}{3\sqrt{3}} + 0.798.
\]

(1)

Figure 1. The normalized voltage (a) and normalized current for three load types: active load (b), load with constant current stabilization (c) and load with power stabilization function (d)

The amplitude of the first harmonic can be obtained from the Fourier series expansion of the current curve and is defined as:

\[
I_{m1} = \frac{4}{\pi} \int_{0}^{\frac{\pi}{6}} \sin(t) \cdot \sin\left(t + \frac{\pi}{6}\right) \cdot dt = \frac{2\sqrt{3\pi} + 9}{6\pi} \approx 1.055
\]

(2)

The RMS current value for the first harmonic is:

\[
I_1 = \frac{I_{m1}}{\sqrt{2}} = \frac{2\sqrt{3\pi} + 9}{6\pi\sqrt{2}} \approx 0.746
\]

(3)

The power factor of a three-phase rectifier with a sinusoidal phase voltage is ratio of the RMS current value for the first harmonic (3) and the total phase current (1):

\[
P_F = \frac{I_1}{I_d}.
\]

(4)

So, the power factor for this mode is defined as:
In order to research the harmonic composition of the current consumed, let us obtain the Fourier series expansion components for the current shape, shown in Figure 1. In this case, the components of the Fourier series expansion can be calculated as:

\[ b_n = \frac{2}{\pi} \int_0^{\pi/6} \sin(n \cdot t) \cdot \sin(t + \frac{\pi}{6}) \cdot dt + \frac{2}{\pi} \int_{\pi/3}^{\pi/2} \sin(n \cdot t) \cdot \sin(t - \frac{\pi}{6}) \cdot dt \]

The RMS current value for other modes is calculated in a similar way. As a result, the power factor (PF) for the load with constant current stabilization is:

\[ PF = \frac{6\sqrt{3}}{\pi\sqrt{6}\sqrt{2}} = \frac{3}{\pi} \approx 0.955. \]

The power factor for the load with power stabilization function is:

\[ PF = \frac{2\int_0^{\pi/6} \sin(t) \cdot \frac{1}{\sin(t + \pi/6)} \cdot dt}{\sqrt{\pi \cdot \ln(3)}} \approx 0.976 \]

The calculated components of higher current harmonics normalized to the first harmonic amplitude, for three modes, described above, with the allowed values according to GOST R 71317.3.2-2006, are given in Table 1 and at the histogram (Figure 2).

Thus, Larionov scheme for three-phase rectifier assumes the current harmonic composition that does not satisfy the GOST requirements for all the modes described.

To eliminate this effect, three-phase power factor correctors can use the active rectifier [12,13, 18, 23, 26] or the Vienna rectifier [14], connected to the three-phase alternating voltage through buffer inductors.

Such devices are implemented as completed modules and can be connected to the power supply before the load. The keys switching algorithm requires hard calculations inside the control system [17, 19, 21, 22] and forms a quasi-sinusoidal current consumption [24, 25]. Such method of transforming the alternating voltage to direct assumes large power dissipation on the switching elements. The keys switching leads to the emergence of high-frequency pulsations in the current. Using of such devices leads to a complication of the system and an increase of its weight and dimensions.

The allowed structure of power factor correction is shown in Figure 3.

The main advantage of this scheme is that the load is connected to the Larionov rectifier through two additional current consumers. The additional current consumers function is special current form consumption. This form depends on the position of the instantaneous voltage vector of each phase. The control system analyzes the load current from the current sense (CS) and the instantaneous voltage vector and generates control signals for the switched rectifiers (SR1 and SR2). In this case, the current of the additional consumers is much less than the total current consumed by the load. It allows one to reduce weight and size of the power factor correction module and achieve results that meet the requirements of GOST R 71317.3.2-2006.
Figure 2. The components of higher current harmonics normalized to the first harmonic amplitude for three modes described above with the allowed values according to GOST R 51317.3.2-2006.

Table 1. Amplitudes of current harmonic components

| № of harmonic component | Value of the harmonic current component, % rated to the first harmonic component | Mode 1 | Mode 2 | Mode 3 | GOST R 51317.3.2-2006 |
|-------------------------|---------------------------------------------------------------------------------|-------|-------|-------|----------------------|
| 2                       |                                                                                 | 0     | 0     | 0     | 2                    |
| 3                       |                                                                                 | 0     | 0     | 0     | 30*PF                |
| 5                       |                                                                                 | 22.65 | 20.04 | 17.32 | 10                   |
| 7                       |                                                                                 | 11.28 | 14.32 | 17.32 | 7                    |
| 9                       |                                                                                 | 0     | 0     | 0     | 5                    |
| 11                      |                                                                                 | 9     | 9.07  | 9     | 3                    |
| 13                      |                                                                                 | 6.45  | 7.71  | 9     | 3                    |
| 15                      |                                                                                 | 0     | 0     | 0     | 3                    |
| 17                      |                                                                                 | 5.69  | 5.89  | 6.06  | 3                    |
| 19                      |                                                                                 | 4.55  | 5.26  | 6.06  | 3                    |
| 21                      |                                                                                 | 0     | 0     | 0     | 3                    |
| 23                      |                                                                                 | 4.08  | 4.35  | 4.59  | 3                    |
| 25                      |                                                                                 | 3.51  | 3.99  | 4.59  | 3                    |
| 27                      |                                                                                 | 0     | 0     | 0     | 3                    |
| 29                      |                                                                                 | 3.22  | 3.45  | 3.64  | 3                    |
| 31                      |                                                                                 | 2.84  | 3.26  | 3.64  | 3                    |
| 33                      |                                                                                 | 0     | 0     | 0     | 3                    |
| 35                      |                                                                                 | 2.65  | 2.9   | 3.03  | 3                    |
| 37                      |                                                                                 | 2.37  | 2.72  | 3.03  | 3                    |
| 39                      |                                                                                 | 0     | 0     | 0     | 3                    |
3. Conclusion

All modes of Larionov scheme load does not ensure the current harmonic composition requirements according to GOST R 51317.3.2-2006.

In order to meet the electromagnetic compatibility requirements, it is necessary to use specialized power factor correctors to ensure that the current shape coincides with the supply voltage shape.

The proposed power factor corrector structure is highly efficient, since it converts only a part of the power transferred to the load.

4. Acknowledgments

The work was supported by Act 211 of the Government of the Russian Federation, contract No. 02.A03.21.0011.

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