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# Input Current Harmonic Distortion of Active Power Factor Corrector Based on Vienne-rectifier

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**ABSTRACT**
The paper contains the questions of nonlinear input current distortions of the active rectifier based on the Vienna-rectifier with different control methods. The quantitative characteristics of nonlinear input current distortions by the value of the neutral wire current (sum of currents) are given.

***Keywords:*** *Electric power industry, Reactive power compensation, Active rectifier, Vienne-rectifier, Total Harmonic Distortion.*

## 1. INTRODUCTION

Today the problem of energy saving is becoming more and more important. Federal laws are passed [1]. According to official data in Russia for 2021, relative to the total energy supplied to the grid, losses amount to about 10 % [2]. The potential for energy saving still remains at a significant level. Therefore, the energy saving will allow not only to obtain significant savings in energy resources by reducing the amount of unproductive energy, but also to increase the energy throughput and reliability of existing power supply capacities. Therefore, energy saving allows not only to obtain significant savings in energy resources by reducing the amount of unproductive energy, also to increase the energy throughput and reliability of existing power supply capacities.

In the process of delivering useful electricity to the consumer, part of this energy is naturally dissipated (spent on delivery). It is possible to enhance transmission lines, transformer substations, other power delivery systems, etc. But this will not be as effective because of the consumer's activity and his impact on the line. In particular, reactive power, which is created by the consumer's electrical appliances and circulates in the power grid, as well as electromagnetic interference emitted by the consumer, all this causes significant losses in the electricity delivery system. In this regard, major consumers use reactive power compensation devices, among which active power factor correctors (active rectifiers) are gaining high popularity today. Despite the high input power factor of such active rectifiers – due to total harmonic distortion (THD) of their input currents, their sum is often significantly different from zero, not to mention radio frequency interference. That also loads not only the power supply lines, but the entire system as a whole and significantly reducing the benefits of energy saving methods. Therefore, in this paper, the dependence of THD of the input current of the active rectifier and the current of the neutral wire of the Vienne-rectifier is considered. That loads not only the power supply lines, but the entire system as a whole and significantly reducing the benefits of energy saving methods. Therefore, in this paper, the dependence of THD of the input current of the active rectifier and the current of the neutral wire of the Vienne-rectifier is considered.

## 2. THE INFLUENCE OF THE REACTIVE POWER IN THE LINE ON THE ELECTRIC POWER LOSS

The transmission of electricity from the power generator to the consumer is accompanied by active losses in transmission lines [3]. Reactive power caused by consumers and/or reactive and active-reactive losses flows, causing additional losses. Thus, the reactive power flow is undesirable and its level must be minimized.

Power line losses can be represented as following:

$$\Delta P = I^2 \cdot R \quad (1)$$

where I – is the k current, R is the active resistance of the line.

It is easy to transform Equation (1), taking into account the line current$I = S/U$, where S is the apparent power of the line, and U is the voltage. The apparent power can be represented as: $S = P/\cos(\varphi)$. Assuming that $\cos(\varphi)$ of the generator and consumer circuits are equal. Also, introducing the assumption that with a change within the limits close to 1 cos (ϕ), the voltage drop ΔU on the active component of the resistance does not change significantly – then Equation (1) can be rewritten to the form:

$$\Delta P = \frac{P_{act}^2 R}{\Delta U^2} \cdot \frac{1}{\cos(\varphi)^2} \quad (2)$$

where $P_{act}$ is the active power. It can be seen that the losses in transmission lines are inversely proportional to the square of $\cos(\varphi)$.

Figure 1 shows the dependence of the percentage reduction of electricity transmission losses on the $\cos(\varphi)$ power transmitted by the power line. If we take $\cos(\varphi)$ equal to 0.85, then an increase in $\cos(\varphi)$ by 0.01, that is, bringing it to 0.86, will reduce losses in the power line by 2.5 %. This is significant, economically attractive and feasible.

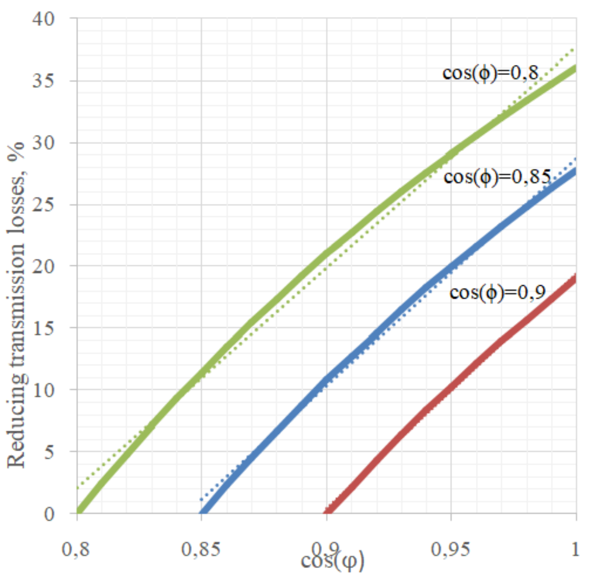


**Figure 1** Dependence of reducing power losses oncos(φ).

## 3. HARMONIC DISTRIBUTIONS OF THE LINES CURRENT

In the previous chapter, the issue of power losses in transmission lines that depend on the power circulating in it was raised. However, higher harmonics, which can also reach large values, have a significant effect on power losses. This effect is not fully studied. There is no generalized information explaining the magnitude and influence of harmonic current distortions on power losses in transmission lines. It seems to be an impossible task. It is impossible to generalize and give the integral characteristics for the higher harmonics of the current circulating in lines for a number of reasons. The harmonic composition is always unstable and will change from measurement to measurement, depending on which consumer is switched on at a given time. For example, this can occur during working hours, when large industrial consumers are in operation, harmonic distortions are at their maximum values.

A transmission line in static mode can be simplified as a long line with parameters, the circuit is shown in Figure 2. In Figure 2, $L_1$ and $C_1$ represent the line inductance and capacitance; $R_1$ – active component of the line resistance; $U_{in}$ – input line voltage; $I_{freq}$ – frequency components of the current generated by the load. The equivalent circuit in Figure 2 is greatly simplified and does not show other reactive elements, for example, for voltage conversion.

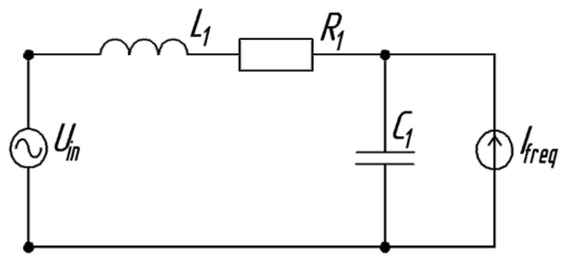


**Figure 2** Transmission line equivalent circuit.

Losses ΔP from harmonic currents $I_{freq\ n}$ can be represented as:

$$\Delta P = \sum_{n=2}^{\infty} I_{freq\ n}^2 \cdot R_n$$

where $R_n$ is the active component of the line resistance at the n-th harmonic. In this case, the resistance of the conductor also depends on the penetration depth of the current into the conductor. The current in a conductor depends on the frequency and material properties. The paper considers the change in resistance due to penetration depth:

$$R = 503\sqrt{\rho/_{\mu \cdot f}}$$

where ρ is the electrical resistivity of the conductor, μ is the magnetic permeability of the conductor or conducting body; f is the current frequency. It can be seen that the active resistance increases with increasing frequency. Also electromagnetic fields are mainly concentrated in the air. Therefore, the inductance and capacitance of the line depends on the frequency weakly, except for their reactance. Perhaps the transformers involved in the power supply are exposed to an even greater detrimental effect of these very harmonic distortions, due to the fact that the induced currents in their steel core, the winding losses and the magnetic reversal losses of the steel core increase. All this can lead to failure of power transformers. Accordingly, we can indirectly talk about a decrease in both their potential service life and their reliability, respectively, the reliability of power supply as a whole.

Figure 3 shows the spectral composition of the voltage in the power supply one of the large industrial consumers in St. Petersburg, Russia. It cannot be said that the spectral composition of a given consumer is always the same. Even at the time of the measurement, the amplitudes of some harmonics differed by several tens of times. But the data were presented at a certain stationary moment, when the spectrum remained practically unchanged. The spectral composition is given up to a frequency of 1 kHz. In Figure 3 it can be seen that the 3rd harmonic of the voltage is at a level of 25 dBV. It is difficult to imagine the magnitude of the currents circulating in the line that can cause such a significant reaction on the resistance. It should be noted that the transmission line sine distortions on the oscilloscope screen were noticeable.

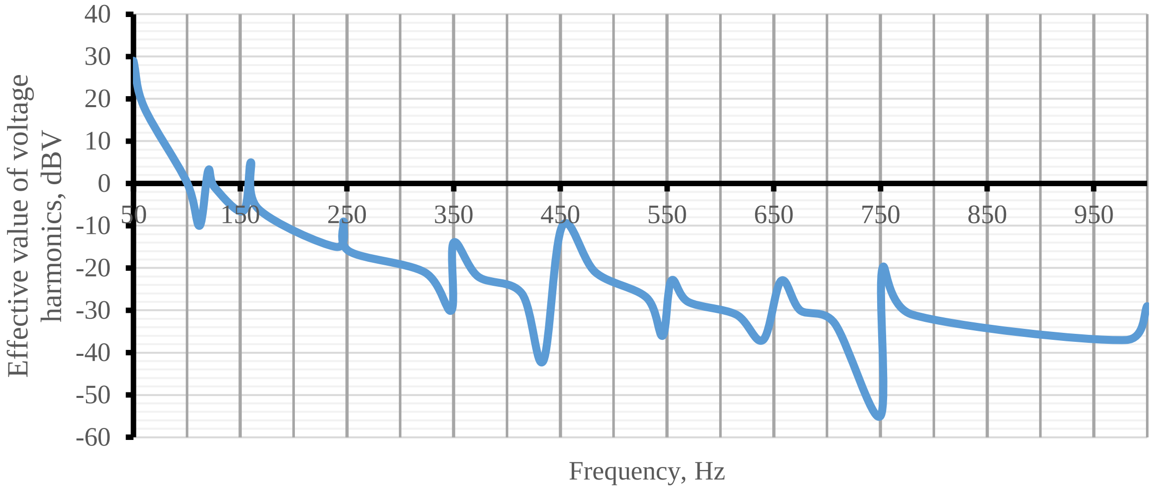


**Figure 3** Spectral composition of line voltage.

## 4. RESEARCH OF A MODEL OF AN ACTIVE POWER FACTOR CORRECTOR BASED ON A VIENNA RECTIFIER

A simulation of the Vienne-rectifier was developed in the LtSpice package. The block diagram in Figure 4 shows the composition and principle of operation of this simulation. The simulation is remarkable in that it uses the properties of real semiconductor elements (transistors, diodes, operational amplifiers, etc.), as well as the parasitic properties of feedback circuit sensors based on static electromagnetic devices. The simulation consists of the following main units: an input low-pass filter based on elements $L_1$-$L_7$, $C_1$-$C_9$; three-phase rectifier based on diodes $D_1$-$D_6$; individual phase control systems $A_1$-$A_3$ based on the PID controller, which controls the PWM controller $A_1$; power transistors $S_1$-$S_3$; output filters $C_{10}$, $C_{11}$; active load $R_1$.

The values of the reactive elements of the filters are selected based on the overall and economic characteristics of a device with a power of up to 40 kW, taking into account their final quality factor. The corner frequencies of the regulator were selected according to the values so that the regulator did not enter the self-excitation mode at frequencies close to the resonant frequencies of the filters, and the overshoot remained at the minimum values.

In this paper, a model of Vienne-rectifier with adaptive control was also simulated, which allows achieving the best operating modes in terms of the qualities of input currents. This is discussed in detail in the works [4]. This paper presents the results of simulating an active rectifier with adaptive control, which was built on the basis of elements with properties close to real in the LTSpice package.

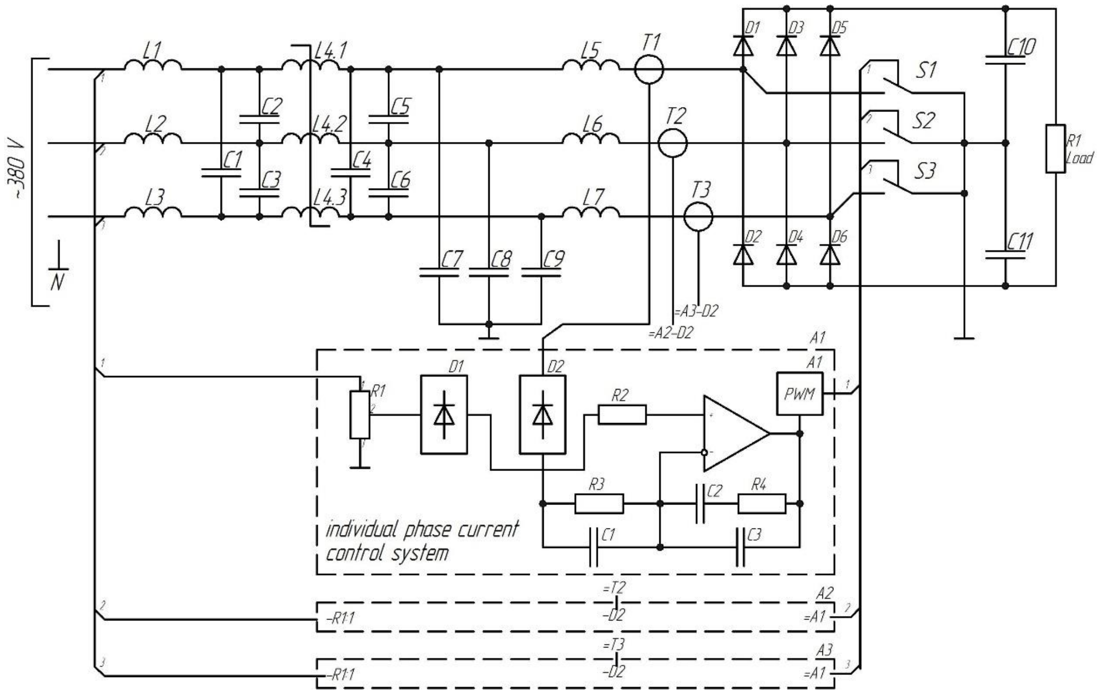


**Figure 4** Structural diagram of the investigated model.

Vienna-rectifier and other active power factor correctors are widely considered in the works of many authors [5], [6]. However, numerical calculations of active correctors, as a rule, are carried out using highly simplified models that practically do not take into account the properties of real semiconductor devices and microcircuits [7]. The use of such models allows achieving very low THD values of the input current and characteristics close to ideal. However, despite the modern equipment in an industrial enterprise, its spectral composition of the mains voltage, which includes active correctors, shows a disheartening picture. In most cases, manufacturers do not indicate enough data in the technical characteristics of the correctors to interpret them from the point of view of the effect on the line: they often stop at the efficiency and the input power factor, which of course is high. Characteristics such as THD or in what frequency range the THD was obtained are usually silent. This is due to the fact that current standards may not restrict the manufacturer. And only those characteristics that are declared by the manufacturer are checked.

In the Vienne-rectifier model, the parasitic parameters of the elements were taken into account through the use of real semiconductor devices and microcircuits models. For example, the distortion parameters introduced by signal rectifiers and used in the control system. These aspects provide a more accurate picture of the rectifier operation. The imperfection of various schemes, including those under different operating modes, was used to achieve different THD values.

The need to take into account the properties of real devices is demonstrated in Figure 5, which shows the voltage diagram during the operation of the signal rectifier. The figure shows a point with a voltage close to zero, in the region of which the greatest distortions are observed. They are much more distorted when converting low-amplitude signals.

Figure 6 shows the output voltage diagram of the signal rectifier. The number “2” indicates the operation of the rectifier, which introduces significant distortion, and under the number “1” of the rectifier with better parameters (close to ideal).

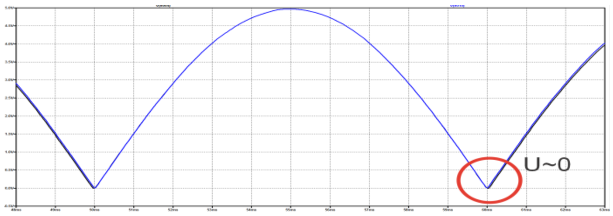


**Figure 5** Operation of the signal analog rectifier.

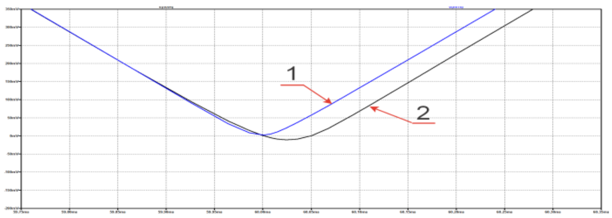


**Figure 6** Operation of the signal analog rectifier at low voltage values.

Figure 6 shows that the voltage diagram of the signal rectifier, marked with the number "2" at a point close to zero voltage, crosses the abscissa axis and takes negative values. This leads to significant distortions of the perturbation in the automatic regulator that controls the PWM controller, and, as a consequence, distortions of the input current of the rectifier.

Figures 7 and 8 show diagrams of phase currents for different principles of building a control system: self-adjusting and based on a PID controller.

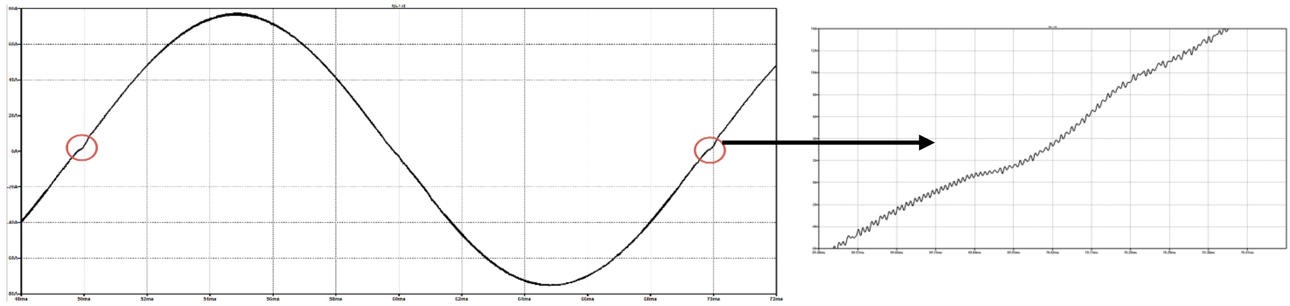

**Figure 7** Operation of an active rectifier with a self-adjusting control system.

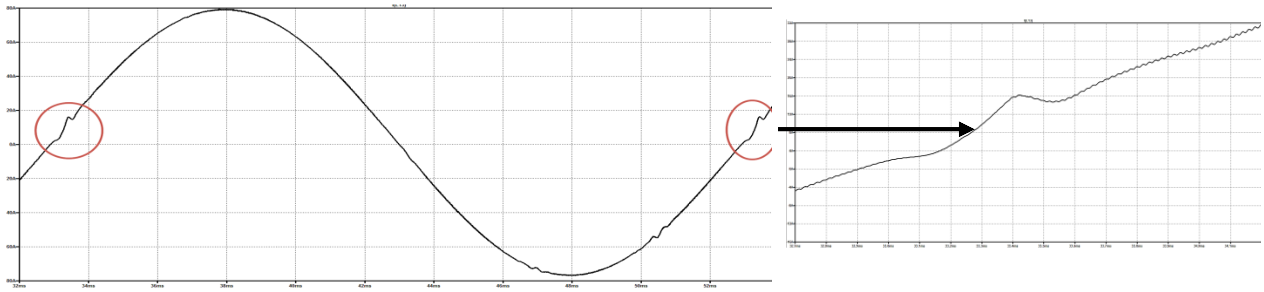

**Figure 8** Operation of an active rectifier with a PID controller in the control system.

In Figures 7 and 8, the main distortions of phase currents are observed at zero values. With PID control, when the current crosses through zero, there is overshoot, leading to the most distortion. As a result, the spectrum of the neutral conductor current takes the form shown in Figure 9. In relation to the mains harmonic, the 3rd, 9th, 15th, 21st, 27th, 33rd and other odd harmonics, listed by arithmetic progression with a step of 6, and harmonics that are multiples of the frequency of the rectifier equal to 50 kHz. The current distortions in each phase generated by the rectifier are not compensated by each other, but add up and flow through the neutral conductor.

According to the results of the study, integral characteristics were obtained that characterize the percentage of the neutral conductor current depending on the phase current (current unbalance) in Figure 10. The dependences shown in Figure 10 were obtained with different control methods: 1 – a system with PID control, 2 – a system with self-tuning.

To calculate THD a different number of harmonics were taken into account. They are marked with a corresponding index: a – up to the 20th harmonic, b – in the entire measured current spectrum (1.3 MHz). THD was changed in several ways: by changing the power consumption of the rectifier; by changing the settings of the regulator; by changing the modes and schemes of operation of the signal circuits of the feedback sensors; by changing the delays in the transmission of the control signal before the control of the power switches.

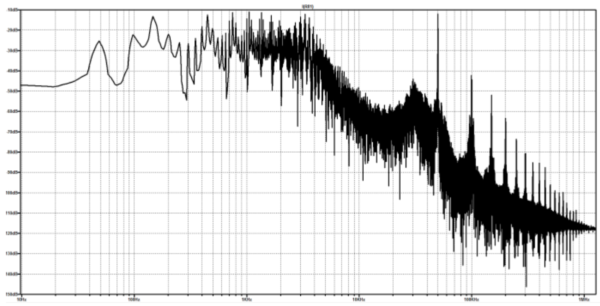

**Figure 9** Current spectrum of the neutral conductor.

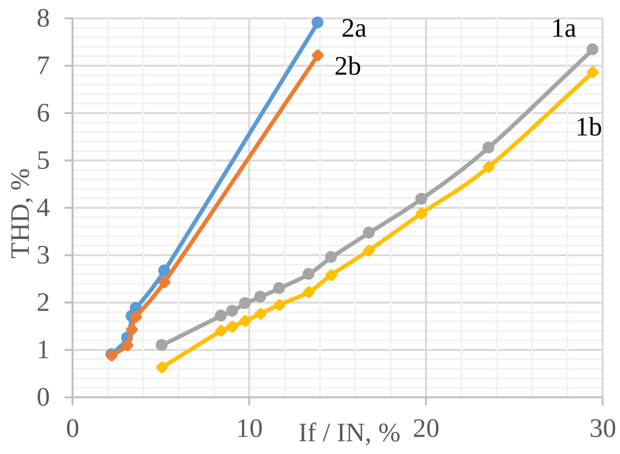


**Figure 10** Dependence of the percentage ratio of the neutral conductor current to the phase current (current unbalance) on the THD of the input current of the active rectifier.

Figure 10 shows a direct relationship between input current THD and phase current unbalance. However, these dependencies are clearly different for different control methods. This suggests that, in addition to the quantitative characteristics of the current distortion, the rectifier control principle affects. For example, when using PID regulation, if THD is taken equal to 5 %, then the neutral wire current will be 23 % of the phase one. With a self-adjusting system, the neutral current will be approximately 10 %. The difference turns out to be significant.

It should be noted that a system with a self-adjusting control system is preferable, due to the fact that, in comparison with a system based on a PID controller, it is less susceptible to self-excitation. This allows the use of filters with higher rejection and the best overall performance of the rectifier.

## 4. CONCLUSION

The paper considered the problems of increasing the energy efficiency of transmission lines by reducing the reactive power circulating in it, as well as reducing the harmonic distortions of phase currents generated by the consumer. At low values of cos(φ) even a slight increase in it can significantly reduce power supply losses. Another important factor is the reduction of harmonic current distortions created by the consumer, due to which mutual partial resonances between the reactive elements can occur.

Active power compensators are not only sources of radio interference, but also the cause of phase current asymmetry due to introduced harmonic current distortion at odd harmonics. In this case, there is a relationship between the current THD and the current unbalance. With different control methods, these dependencies turn out to be different and begin to converge only at very low THD values. This indicates the need for additional characteristics in terms of the asymmetry of their input current, generalizing nonlinear distortions.

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