Analysis of non-sinusoidal voltage at metallurgical enterprises

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Abstract. The article presents the results of the study of non-sinusoidal voltage in the power supply system of non-ferrous metallurgy enterprises. The non-sinus voltage coefficients are calculated for the operation of valve inverters and welding machines. The range analysis of the noah caste of higher harmonic components by voltage was carried out and it was established that the values of the correlation coefficients between the non-sinusoidal coefficients of voltage and the fraction of noah and pointer castes of electricity consumers for the production of hard alloys are equal to: 0.56 and 0.37, which makes it possible to limit the range of priority tasks for calculating the required filter-compensating devices. It is necessary to conduct further studies of higher harmonics in the system of power supply of industrial enterprises and the development of methods for calculating and optimal distributing filter-compensating devices in enterprises.

1. Introduction
At modern industrial enterprises, non-linear loads have become widespread. These include, first of all, various types of valve inverters, mainly thyristor, electric arc and electric resistance welding plants, electric arc steelmaking and ore heat-treating furnaces, gas-discharge lamps, power magnetic amplifiers and transformers. These loads consume current from the network, the curve of which turns out to be non-sinusoidal, and in many cases non-periodic; as a result, non-linear distortions of the mains voltage curve or, in other words, non-sinusoidal modes occur.

Non-sinusoidal modes adversely affect the operation of power electrical equipment, systems of relay protection, automation, telemechanics and communications. The economic damages arising from the impact of higher harmonics are mainly due to the deterioration of energy performance, reduced reliability of electrical networks and reduced service life of electrical equipment. In some cases, there is deterioration in quality and a decrease in the number of manufactured products. Therefore, the progressive introduction of a valve drive and electrical technology has led to the importance and relevance of solving the problem of higher harmonics in electrical networks.

The main range of issues that make up the content of this problem comes down to the following: assessment of the electromagnetic compatibility of sources of higher harmonics and other loads, i.e. the effect of harmonics on electrical installations, and the resulting economic damage; quantification of higher current harmonics generated by various non-linear loads, and prognosis of the values of higher current and voltage harmonics in electrical networks; decreasing levels of higher harmonics [1–9].
2. Characteristics of non-sinusoidality contributor in the power supply system of an industrial enterprise

One of the largest non-ferrous metallurgy enterprises in RNO-Alania is Pobedit OJSC. The main products of the plant are hard alloys, tungsten and molybdenum billets. The most energy-intensive is the power building, in which the consumers of the noah caste of the rank $H$-distribution are concentrated: electrolyzers FB-500 M; $n_1 = 6$; gas blowers VK-50; $n_2 = 2$; calcining furnaces; $n_3 = 5$; compressors 202 GP 20/2; $n_4 = 3$. Let us evaluate the level of higher harmonics for the transformer-converter unit of the electrolysis units of the power building of Pobedit OJSC. A transformer TDNPV-12500/10-U1 and converter unit VAKV2-12500/450 are installed at the substation of the power building, the parameters of which are $S_t = 6800$ kVA, $U_2 = 375$ V, $u_k = 11\%$, $U_d = 450$ V, $I_d = 26250 = 12500$ A, $\eta = 97\%$, $\cos \phi = 0.93$. The converter is made with a push-pull circuit of the sequential type, equivalent to the twelve-phase rectifying mode $m = 12$, as a result of which the current and voltage curves contain the 11, 13, 23, 25th harmonics.

The main contributor of the non-sinusoidal distortion of the voltage in the power supply system (PSS) of the enterprise are the semiconductor silicon converters of the type VAKV2-12500-450, designed to rectify the current in electrolyzers of the type FV-500M, in which the distilled water is decomposed into hydrogen and oxygen. Hydrogen is the main reducing agent in the production of hard alloys in resistance furnaces and welding machines. The rated power of the electrolyzers is 2993 kW. The replacement scheme of the power supply plant is shown in Figure 1.

![Substitution scheme of the enterprise power supply system](image)

Figure 1. Substitution scheme of the enterprise power supply system

Figure 1 shows the calculated values of system resistances ($x_{\text{system}}$) and converter ($x_{\text{converter}}$) in relative units, power consumed by the converter ($S_{\text{converter}}$) and its power factor ($\cos \phi$). The effective values of the 11th, 13th, 23rd and 25th harmonics and the sinusoidal distortion coefficient of the voltage curve $k_U$ are determined:

\[ U_n = \lambda_\gamma \frac{m \Delta U_1}{6 \sqrt{2}}, \]

\[ k_U = x_{\text{system}} \left( \frac{3}{\pi} \cdot \frac{\sin \phi}{x_{\text{system}} + x_{\text{converter}}} - \frac{9}{\pi^2} \right), \]

where $\lambda_\gamma$ is the coefficient determined depending on the angle of commutation of the converter $\gamma=0.17$ for the $n$-th harmonic; $\Delta U_1$ is the depth of the main commutation distortion, $\Delta U_1 = 1.25$ kV.

The calculated values of the parameters are: $k_U = 4.84\%$; $U_{11} = 0.25$ kV; $U_{13} = 0.23$ kV; $U_{23} = 0.12$ kV; $U_{25} = 0.14$ kV.
3. Results of studies of non-sinusoidal voltage on the buses of the switchgear of the enterprise with valve converters

As a result of the research, the values $k_U$ and $k_{U(n)}$ for interfacial voltages at different load currents ($I_{\text{load}}$, A) of a single rectifier unit [10-12] were determined.

The amplitude-frequency spectrum of harmonic oscillations of phase-to-phase voltages of normative normal $k_{U(n)\text{normal}}$ and maximum permissible values $k_{U(n)\text{limit}} = 1.5 \cdot k_{U(n)\text{limit}}$ are shown in Figure 2. The total values $k_U$ and $k_{U(n)}$ of electrolyzers receiving power from 4-6 rectifier units, may exceed the maximum permissible values.

![Figure 2. Amplitude-frequency spectrum of harmonic oscillations](image)

| harmonic number | kU(n) between A and B | kU(n) between B and C | kU(n) between C and A |
|-----------------|-----------------------|-----------------------|-----------------------|
| kU(n) normal    |                       |                       |                       |
| kU(n) limit     |                       |                       |                       |

Figure 2. Amplitude-frequency spectrum of harmonic oscillations

It is established that the values $k_U$ are respectively:

$k_{UA-B} = 2.7 \%$; $k_{UB-C} = 2.6 \%$; $k_{UC-A} = 2.4 \%$.

Let us check the non-sinusoidal coefficient using the calculation formula, taking into account the three-phase short-circuit current on the buses of the switchgear with voltage 110 kV. According to the power system, the value of the three-phase short-circuit current (s.c.) on the substation buses (PS) RP 110 kV is $I_{s.c.} = 10.3$ kA. The non-sinusoidal ratio of electrical networks with valve converters is calculated by the formula:

$$k_U = \frac{S_{\text{nominal convert}}}{{S_{\text{short circuit}}}} \sqrt{\frac{0.955 \cdot \sin \phi}{S_{\text{convert}}} - 0.91},$$

where $x_{\text{converter}}$ is the inductive resistance of the converter unit. The formulas feature the parameters of the power supply system of JSC Pobedit, the supply transformer and the valve converter. The calculated value of the non-sinusoidal coefficient amounted $k_U = 6.7 \%$, i.e. exceeds the permissible requirements of GOST $k_U = 5 \%$, and therefore in the PSS it is necessary to install filter-compensating devices (FCD), providing compensation for the deficit of reactive power of the main frequency, filtering higher harmonics, and balancing the network voltage. FCD is placed in the node connecting the nonlinear load. The total reactive power generated by the filters is selected from the condition of the balance of reactive power in the load node.

In the course of performing the calculations, it was obtained that the power of the filter-compensating device generated to compensate for the reactive load of consumers is 3.2 MVAr. The higher harmonic currents of the valve converter are: $I_{11} = 50.4$ A, $I_{13} = 43$ A.

According to the calculated filter power values and harmonic currents, filters F11-10-1600 and F13-10-1600, $I_n = 80$ A were selected. The total power of the filters $Q_{\text{FCD}} = 3200$ kVAR. To check the results of the calculations, experimental measurements of $k_U$ were made on RU 6 kV buses. The measurements were carried out using the PKK-57 complex control device.

According to the results of experimental measurements, the value of the non-sinusoidal coefficient on 6 kV switchgear buses is $k_U = 7.1 \%$, which agrees quite well with the calculated value. The spectrum...
of voltage and current harmonics contains only odd harmonics and the most pronounced of them are the 11th, 13th, 23rd, 25th harmonics.

4. Results of the studies of non-sinusoidal voltage at the plant with welding machines

One of the most important technological conversions, in which the production of tungsten billets is carried out, is the shop of refractory metals No. 1. The main equipment of the workshop is resistance furnaces (rotating (VKP), 13 pipe (TP), muffle) and welding machines. Using the devices AR5, PKK-57, Energotester PKE, the non-sinusoidality of voltage and current arising during operation of welding machines was studied [10–14].

Welding machines TSEP-223A are intended for welding tungsten billets. To ensure the required welding temperature of 2200–2400 °C, direct heating of the billets is used through an OSU 100/0.5 type step-down transformer or OSU 200/0.5, providing output values $U_2=18$ V, $I_2=4.7$ kA. Figure 3 shows the histograms of the changes in $k_{U12(n)}$, $k_{U23(n)}$ of the welding machines TSEP-223A.

![Histograms of change $k_{U(n)}$](image)

**Figure 3.** Histograms of change $k_{U(n)}$

From Figure 3 it can be seen that during the operation of welding machines, harmonics arise with voltage $n = (3–35)$, while the value $k_{U(n)}$ varies from 0–67.58 %, the most influenced are 3, 5, 7, 9, 11 and 13 harmonics.

The values of voltage non-sinusoidal coefficients ($k_U$), are determined, which for welding machines are: $k_{U12}=33.82$ %, $k_{U23}=76.59$ %. The value of $k_U$ in the PSS of welding machines significantly exceeds the normally acceptable values of $k_{U\text{ normal}} = 8$ % at $U = 0.38$ kV.

5. Results of studies of non-sinusoidal voltage at the enterprise with welding machines

It is necessary to tighten the requirements for HH voltage to the required $k_{U\text{allow}}=2$%. Therefore, already now at the enterprises of non-ferrous metallurgy it is necessary to conduct additional studies of the HH and the development of measures to reduce non-sinusoidal voltage. Based on the analysis of HH for all castes of consumers of carbide production, the rank distribution of HH is constructed, shown in Figure 4.

From figure 4 it is clear that HH are ranked as follows: HH with $n = 13, 11, 5$ — noah caste; HH with $n = 17, 3, 7, 19$ — pointer caste and HH with $n = 9, 23, 15, 25$ — locust caste.

Figure 5 shows the dependences of $k_U$ and $W$ on the rank of consumers ($k_U = f(\text{Rank})$, $W = f(\text{Rank})$) for consumers of noah (rank 1–6) and pointer (rank 7–11) distribution castes.

The correlation coefficients between the total value of the $n^{th}$ harmonic component of the voltage ($k_{U(n)}$, %), the voltage non-sinusoidality coefficient ($k_U$, %) and the share of the noah and pointer castes of electricity consumers ($W$, %) are 0.56 and 0.37 respectively.
Figure 4. Rank distribution of HH across all castes of carbide consumers

Figure 5. Dependencies $W = f(Rank)$, $k_U = f(Rank)$

6. Conclusion
The method for the experimental study of the amplitude-frequency characteristics of the HH voltage in the 6 kV PSS Pobedit JSC has been developed. The analysis showed that the values of $k_{U(n)}$ and $k_U$ of individual non-linear consumers exceed the values allowed by GOST.

The range analysis of the voltage of the noah caste of HH by voltage ($n = 11, 13, 5$) was carried out and it was established that the values of the correlation coefficients between $k_{U(n)}$, $k_U$ and the share of noah and pointer castes of electric power consumers ($W, \%$) for carbide production are: 0.56 and 0.37, which allows us to limit the range of priority tasks for calculating the required FCD.

It is necessary to conduct further studies of HH in PSS of industrial enterprises and the development of methods for calculating and optimally distributing FCD in PSS of 6 kV of non-ferrous metallurgy enterprises.

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