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Experimental and Analytical Study of Highest Harmonic Components of Voltage of Industrial Enterprises

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***Abstract*—During the implementation of energy efficiency policy in the Russian Federation, issues related to the analysis of the electric power quality (QE) in the power supply systems (PSS) of industrial enterprises are of particular importance. Much attention has been paid in recent years to the problem of the electric power quality both in our country and abroad due to significant economic damage caused by deterioration of QE indicators. The improvement of the main indicators is an integral part of the energy and resource saving policy, the role and importance of which are ever increasing as part of the implementation of the country's energy program. In the course of work, comprehensive studies of electric power quality indicators were carried out using modern measuring devices (AR5, PKK-57), their further analysis using software (DELPHI, MathCad, Excel) and criterial evaluation of theoretical and experimental studies. A method of experimental study of the amplitude-frequency characteristics of the higher voltage harmonics in the 6 kV power supply system of OJSC Pobedit and OJSC Electrozink has been developed. Comparison of experimental data on the harmonic components of currents and voltages and the data of analytical calculations in Fourier series have shown good convergence of the results. The results of the study of non-sinusoidal voltage in the power supply systems, according to the developed calculation methods, were introduced into production at the enterprises of non-ferrous metallurgy of the Republic of North Ossetia-Alania: OJSC Electrozinc (zinc production), OJSC Pobedit (hard-alloy production).**

Keywords—non-sinusoidal voltages; power supply system; power quality

I. Introduction

The purpose of the work is to conduct experimental studies of the electric power quality for individual technological processes for production of non-ferrous metals; processing and analysis of experimental data; theoretical justification of the results of experimental studies; development of adequate mathematical models of electric power quality indicators.

The shape of the curves of instantaneous values of voltages and currents in time in electric power networks is always more or less different from a sinusoid. This is due to a number of reasons, starting with the non-sinusoidal voltage of the generators, caused by the non-sinusoidal distribution of induction in the air gap. However, the undoubted reason for the non-sinusoidal voltages and currents at the present time is so-called non-linear high-power receivers installed at industrial-manufacturing consumers. Nonlinear load consumes non-sinusoidal current with a discrete or continuous frequency spectrum. Nonlinear high-power loads for industrial-manufacturing consumers are primarily uncontrolled silicon diodes and controlled rectifiers (thyristors) for various applications. With a widely used connection of diodes and thyristors in three-phase bridge circuits, the essential property of a rectifier is the number of bridges and the group of connections of rectifier transformers that determine so-called number of converter phases, i.e. the composition of the frequency spectrum of its current, and thus the degree of its influence on the network as a source of high harmonics (HH).

One of the most important aspects in the field of QE improvement is the development of methodology for determining the level of emission of higher harmonic components, and the identification of the voltage distortion source in PSS of industrial enterprises.

The task of the research is the development of a methodology for the experimental study of the amplitude-frequency characteristics of the HH voltage in the power supply system of non-ferrous metallurgy enterprises.

II. Experimental Research Techniques and Analytical Calculation of Higher Harmonics

The paper provides results of a comprehensive study of the power consumption parameters (energy audit) of the two largest non-ferrous metallurgy enterprises of the Republic of North Ossetia-Alania - Electrozinc OJSC (zinc production) and Pobedit OJSC (production of hard alloys). Based on the results of the energy audit, a cluster of tasks is formed, the solution of which is aimed at energy saving and increasing the efficiency and reliability of the equipment. The electricity quality study is based on the specially developed technique for experimental investigation and analytical calculation of higher harmonics voltage and current in power supply systems [1-15].

At the enterprises of Electrozinc OJSC and Pobedit OJSC there is a large number of non-linear electric receivers - rectifier converters, induction furnaces, etc., which, due to generating higher harmonics, seriously degrade electricity quality in power supply systems by parameters characterizing the voltage non-sinusoidal. According to [16-23], electricity quality by the non-sinusoidal voltage criterion in power supply systems is characterized by two indicators $k_{U(n)}$ and k_U.

The authors exemplified the results of an experimental study of the higher harmonics current and voltage components of electric furnaces in the process of hydrogen heating during the production of hard alloys at Pobedit OJSC and the analytical calculation of the higher harmonics components based on the expansion of the obtained dependences into Fourier series.

The specificity of hard alloys production implies creating a restoring environment in electric furnaces by means of technological gas, hydrogen, which is produced in the power building. The required quality of hydrogen is accomplished via purification and drying facilities, the calcining furnaces of which are the most energy consuming.

The temperatures in the furnaces within 420°C÷ 470°C is maintained automatically by relevant sensors emitting control impulses to the control electrodes of the non-contact switch thyristors, turning furnace electric heaters on and off. In connection with heating hydrogen in calcining furnaces and the presence of a thyristor regulator in its circuit, which has a nonlinear voltage-current characteristic, non-sinusoidal modes occur, which lead to the appearance of higher harmonics currents and voltages that distort the sinusoidal shape of the voltage curve at the load knots .

In the framework of a comprehensive energy survey at Pobedit OJSC using a PKK-57 device, a study of the non-sinusoidal currents and voltages in the power supply of furnace was carried out, and an oscillogram of phase voltage changes (Fig. 1) and phase currents $I_{ph}=f(\omega t)$ was obtained (Fig. 2) [24-32].

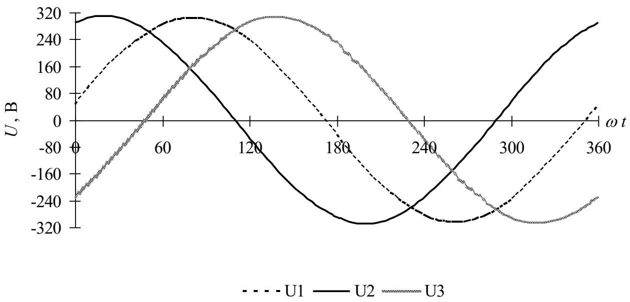

Fig. 1. The oscillogram of phase voltage changes $U_{ph}=f(\omega t)$.

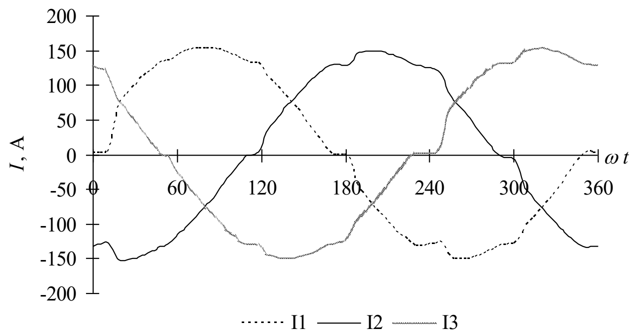

Fig. 2. The oscillogram of phase currents changes $I_{ph}=f(\omega t)$.

The analytical calculation of the higher harmonics is carried out on the basis of the expansion of the dependences $U_{ph}=f(\omega t)$ in Fourier series.

The shape of the non-sinusoidal voltage curve is described by the periodic function $U_{ph}=f(\omega t)$, where $\omega = 2\pi f_c$ is the circular frequency of the supply voltage, f_c=50 Hz, which can be expanded in Fourier series. Accordingly, the function $U_{ph}=f(\omega t)$ can be represented by a series of harmonic components:

$$U(\omega t) = A_0 + \sum_{n=1}^{\infty} \left(A_n \cos n\omega t + B_n \sin n\omega t \right). \qquad (1)$$

A general form for n harmonics:

$$U(\omega t) = A_0 + \sum_{n=1}^{\infty} A_n \sin(n\omega t + \varphi_n), \quad (2)$$

where $A_0 = \frac{1}{2\pi}\int_0^{2\pi} U(\omega t)d\omega t$ is a constant component; $A_n = \frac{1}{n}\int_0^{2\pi} U(\omega t)\cos n\omega t d\omega t$; $B_n = \frac{1}{n}\int_0^{2\pi} U(\omega t)\sin n\omega t d\omega t$ are integral functions; φ_n is the initial phase of the harmonic component: $\varphi_n = arctg\left(\frac{B_n}{A_n}\right)$.

When determining the harmonics of Fourier series with the help of a graphical method, it is necessary to replace a definite integral by the sum of a finite number of terms. For this purpose, the period of the function $U=f(\omega t)$, equal to 2π, is divided into p equal parts: $\Delta U=2\pi/p$, and integrals are replaced by sums. On this basis, the following is obtained:

$$A_0 = \frac{1}{p}\sum_{i=1}^{p} U_p(\omega t); \quad (3)$$

$$A_n = \frac{2}{p}\sum_{i=1}^{p} U_p(\omega t)\cos_p n\omega t; \quad (4)$$

$$B_n = \frac{2}{p}\sum_{i=1}^{p} U_p(\omega t)\sin_p n\omega t. \quad (5)$$

To decompose the resulting curve in Fourier series into individual harmonics, the frequency period was divided into 128 intervals (p=128). Since the graph of the change in the instantaneous voltage values is symmetrical about the abscissa axis, A_0=0 and the series will consist only of odd harmonics. In accordance with the foregoing, with the help of the mathematical apparatus of the program MathCAD, equations for phase voltages are derived.

Fig. 3 shows the harmonic composition of the voltages in the form of a histogram of changes in the average values $k_{Ui(n)}$ of the phase voltages (i is the phase number, i=1, 2, 3; n is the harmonic number).

It can be seen in Fig. 3 that in individual phases, harmonic components with voltages of 3rd, 5th and 7th numbers are observed, the value $k_{U(n)}$ varies from 0 to 1.09%. The values k_U for the individual phases were: k_{U1}= 0.91%; k_{U2}= 1%; k_{U1}= 1.2%, i.e. do not exceed normative data. The harmonic composition of the phase currents, obtained with the help of PKK-57, is shown in Fig. 4.

It can be seen in Fig. 4 that, in some phases of the furnace, harmonics up to order 27 are observed, their percentage with respect to the fundamental harmonic component ranges from 0 to 4.47%. The greatest influence is exerted by harmonics of the 5th, 7th and 11th numbers.

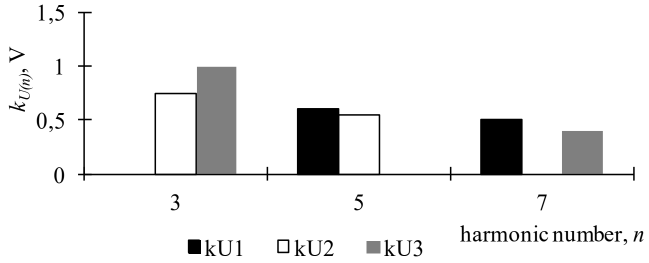

Fig. 3. The histogram of changes in the mean values $k_{Ui(n)}$.

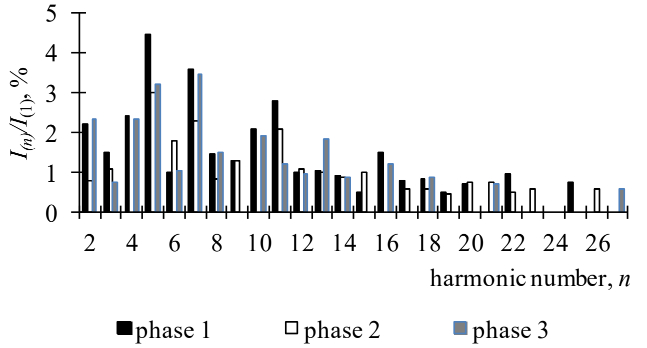

Fig. 4. The harmonic composition of the phase currents ($I_{ph(n)}$) with respect to the fundamental harmonic component ($I_{(1)}$).

By analogy with the formula (2), the dependences $I_{ph}=f(\omega t)$ were also expanded in Fourier series in the n-th harmonic components of the phase currents.

A comparison of the experimental data on the harmonic components of currents and voltages and the analytical calculation data, made on the basis of the expansion of the functions $U_{ph}=f(\omega t)$ and $I_{ph}=f(\omega t)$ into Fourier series, showed acceptable convergence of the results.

III. Technique for Determining the Actual Contribution of the Consumer (ACC) and System (ACS) in the Unsinusoidality of the Power Supply System Voltage in Enterprise on the Basis of an Active Experiment - Turning on Main Step Down Substation Transformers on a Parallel

The problem of voltage unsinusoidality at the point of common coupling of electrical system – a power supply system of enterprise (main step down substation) arises when there are mainly non-linear consumers in the power supply system generating higher harmonics (HH) in the point of common coupling (PCC).

If there are several nonlinear or asymmetrical consumers connected to one node, then the question arises about the share of each of them in the total voltage distortion in the point of common coupling. Moreover, for each individual consumer, all other consumers are included in the electrical system. In order to say how guilty this particular consumer is in distorting the sinusoidal voltage, it is necessary to determine the actual contribution of the consumer (ACC) and the actual contribution of the system (ACS) to the point of common coupling.

The problem of determining the ACC and the ACS is not only a scientific problem, but also an economic one, since for the deterioration of the quality of electricity above the standards given in GOST, it is possible to apply various kinds of sanctions. The criterion for determining the guiltiness (innocence) in the distortion of the sinusoidal voltage in the point of common coupling is the ratio between the preset acceptable contribution of the consumer and the calculated ACC of the consumer.

There are a number of methods for the determination of ACC and ACS, which are not always convenient for practical use.

The developed technique with using the active experiment - short-term (within a few seconds) switching on the transformers on parallel operation allows switching the on/off section switch remotely from the control room. The probability of a short circuit in the period of parallel operation of transformers for reading $I(t)$, $U(t)$ is negligible and can be neglected. The technique is widely used since large enterprises of non-ferrous metallurgy belonging to the I-st category of consumer reliability have at least two transformers on the main step down substation. The developed technique allows calculating the resulting resistances of the *n-th* harmonic component of the voltage $Z_{res(n)}$ in the the point of common coupling based on the measurement of current and voltage parameters before and after switching on two transformers on parallel operation. The equivalent scheme of power supply system replacing related to the point of common coupling for the determining ACC and ACS is shown in Fig. 5.

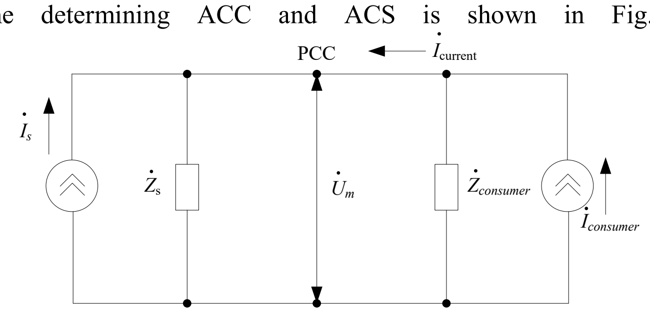

Fig. 5. Equivalent scheme of replacing the power supply system related to the point of common coupling

In Fig. 5, the following notations are used:

$\dot{I}_s$ – harmonic component of the equivalent source of current distortion from the electrical system;

$\dot{I}_{consumer}$ – the harmonic component of the current source of distortion of the nonlinear consumer;

$\dot{I}_{current}$ – harmonic component of the current in the consumer's power supply circuit;

$\dot{Z}_s$ – equivalent linear resistance of the electrical system for a given harmonic component;

$\dot{Z}_{consumer}$ – resistance of the linear part of the consumer load for a given harmonic component;

$\dot{U}_m$ – harmonic component of voltage in the point of common coupling.

The measurement and calculation algorithm: a) measures the currents $I_{T(n)1}$ and the voltage $U_{m(n)1}$ in the normal mode of operation of one transformer (index 1 indicates the initial, start value of the current and voltage parameters, n is the harmonic number); b) the currents $I_{T(n)2}$ and voltages $U_{m(n)2}$ are measured after short-time switching on of the second transformer on parallel operation (index 2 indicates the value of the current and voltage parameters after switching on the second transformer); c) the resulting resistance $Z_{res(n)}$ is determined in the point of common coupling when switching on the second transformer, ACS, ACC by the calculated values of voltage changes ($\Delta U_{T(n)} = U_{T(n)2} - U_{T(n)1}$) and current ($\Delta I_{T(n)} = I_{T(n)2} - I_{T(n)1}$).

A mathematical model for calculating the resulting resistance in the point of common coupling $Z_{res(n)}$:

$$Z_{res(n)} = \frac{\Delta U_{T(n)}}{\Delta I_{T(n)}} . \tag{6}$$

The calculated changes in voltage $\Delta U_{T(n)}$ and current $\Delta I_{T(n)}$ in the point of common coupling can have different signs. When $Z_{res(n)}<0$, we get the input impedances of the consumer $Z_{п(n)}$, when $Z_{res(n)}> 0$ - the input resistances of the electrical system $Z_{c(n)}$.

ACS and ACC in unsinusoidal voltage in the point of common coupling are determined by the expressions:

$$U_{acc(n)} = \frac{\left(U_{T(n)} + Z_{consumer(n)} \cdot I_{T(n)}\right)}{Z_{s(n)} + Z_{consumer(n)}} \cdot Z_{s(n)} ; \tag{7}$$

$$U_{acs(n)} = \frac{\left(U_{T(n)} - Z_{s(n)} \cdot I_{T(n)}\right)}{Z_{s(n)} + Z_{consumer(n)}} \cdot Z_{consumer(n)} . \tag{8}$$

IV. Conclusion

A method for experimental study of the amplitude-frequency characteristics of the higher harmonics voltage in a power supply system with 6 kV voltage has been developed at Pobedit OJSC and Electrozink OJSC. The analysis showed that the values $k_{U(n)}$ and k_U of individual non-linear consumers exceed the allowed values.

A method has been developed for determining the ACC and ACS in voltage unsinusoidality based on an active experiment - short-term switching on the power transformers of the main step-down substation to parallel operation.

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