ATLANTIS PRESS
Advances in Engineering Research, volume 182
VIII All-Russian Science and Technology Conference "Contemporary Issues of Geology, Geophysics and Geoecology of the North Caucasus" (CIGGG 2018)

Rank Analysis of Higher Harmonics Voltage Spectrum of Metallurgy Enterprises

Roman V. Klyuev
Industrial Power Supply Department
North Caucasian Institute of mining and metallurgy (State Technological University), NCIMM (STU)
Vladikavkaz, Russian Federation
kluev-roman@rambler.ru

Igor I. Bosikov
Applied Geology Department
North Caucasian Institute of mining and metallurgy (State Technological University), NCIMM (STU)
Vladikavkaz, Russian Federation
igor.boss.777@mail.ru

Oksana A. Gavrina
Industrial Power Supply Department
North Caucasian Institute of mining and metallurgy (State Technological University, NCIMM (STU)
Vladikavkaz, Russian Federation
Gavrina-Oksana@yandex.ru

Vladimir Ch. Revazov
Department of Philosophy and Socio-Legal Disciplines
North Caucasian Institute of mining and metallurgy (State Technological University), NCIMM (STU)
Vladikavkaz, Russian Federation
revazov.v@yandex.ru

Mariet Z. Madaeva
Department of heat engineering and hydraulics
Grozny State Oil Technical University named after academician MD Millionshtchikov (GSOTU)
Grozny, Russian Federation
mareta0100@mail.ru

Abstract— **The issues related to determining the non-sinusoidal voltage coefficients at large industrial enterprises of non-ferrous metallurgy with a high specific weight of non-linear loads containing higher harmonics voltage components require special attention. The questions concerning development of an experimental research technique of amplitude-frequency characteristics of the higher voltage harmonics in power supply systems of industrial enterprises of non-ferrous metallurgy are considered in the article. A rank analysis of the higher voltage harmonics of Noah's caste spectrum has been conducted. This analysis shows that correlation coefficients between non-sinusoidal coefficients of the Noah's share and pointer caste shares of energy consumers for non-ferrous metallurgy enterprises are 0.56 and 0.37, respectively. Further research of non-sinusoidal voltage in power supply systems of industrial enterprises is highly recommended.**

Keywords*— *non-sinusoidal voltages; rank analysis; power supply system.

I. Introduction

Any introduction of new technological equipment unequivocally imposes stringent requirements on electricity in power supply systems of industrial enterprises.

One of the most important indicators of quality of electricity is the non-sinusoidal voltage. Scientific publications, devoted to the study of non-sinusoidal voltage, have been accumulated for dozens of years by now [1-5]. The analysis of works in the field of research of qualitative indicators of power consumption has shown insufficient study of the issues related to the analysis of non-sinusoidal voltage at the enterprises of non-ferrous metallurgy with a large specific weight of non-linear loads. The non-sinusoidal voltage distortion coefficients (k_U) and the coefficients of the n-th voltage harmonic component ($k_{U(n)}$) that are currently set by the regulatory documents should be significantly reduced, from the permissible value of 5% to 2% [6, 7].

The total harmonic distortion of the phase-to-phase voltage form is determined by the formula:

$$k_U = \frac{\sqrt{\sum_{n=2}^{N} U_{(n)}^2}}{U_{(1)}} 100 \qquad (1)$$

where $U_{(n)}$ is the current value of the n-th harmonic voltage component; $U_{(1)}$ is the current value of the fundamental frequency voltage; n is the number of the harmonic voltage component; N is the number of the last of the considered harmonic voltage components.

The enterprises that deteriorate the quality of electricity can be imposed economic sanctions in case of non-compliance with regulatory requirements. Therefore, it is relevant to develop a methodology for a comprehensive assessment of the quality of electricity that will make it possible to monitor the quality of electricity.

II. Materials and Methods

An experimental study of higher harmonics and power quality was carried out applying the AR-5 power analyzer, the PKK-57 complex control device and the PKE Energotester with an accuracy class index of 1.0.

In separate neutral and earth of a power transformer, phase voltage values are not calculated. In this case only voltage between phases (U_{12}, U_{23}), current values in phases (i) (I_i) and total power values are calculated. Whereas, one of these three phases (for example, phase 2) is taken as the reference (basic) one for comparison. The total values of active, reactive and full power are indicated on the display as the sum of the values measured by the following instruments: a wattmeter, a varmeter, a VA meter (Fig. 1).

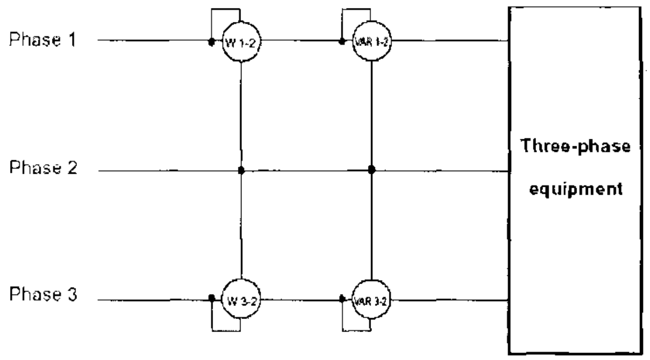

Fig. 1. The principle of connecting the device to the system without using the neutral conductor.

The scheme of connecting the device in a three-phase three-wire system is shown in Fig. 2.

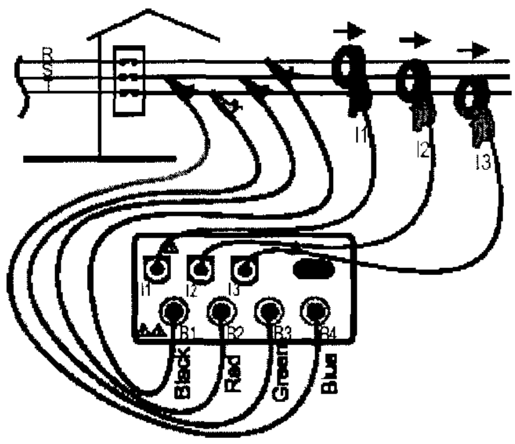

Fig. 2. The scheme of connecting PKK-57 in the three-phase three-wire system.

The device carried out the measurements in the analyzer mode (ANALYZER). In this mode, the device allows one to implement the following functions:

a) real time display (in numerical values or form) of the electrical supply voltage parameters in single-phase and three-phase power supply systems (with and without neutral earthing) and analysis of harmonic components of voltage and current*;*

b) direct instant *measurement of energy* (without saving data);

c) data maintainance - saving the measured current parameter values into the internal memory of the device in the graphic form*;*

d) simultaneous recording of mean-square values of voltage and current; their corresponding harmonics (k(U)n, k(I)n, where n is the harmonic number); power values: active (P), reactive: inductive (QL), capacitive (Qc), full (S); cosφ by inductive (cosφL) and capacitive (cosφc) loads; energy consumption: active (Wa, watt-hour), reactive, (Wp(L), Wp(c), varhour), full (W, VAhour), voltage anomalies (recording overvoltage impulses, voltage dips, frequency deviations, short-time overvoltage, etc.) with a 10 ms time resolution.

Mathematical processing of research results on representative samples (n>30) $k_{U(n)}$ was carried out with the appliance of the Statistical Processing of Experimental Data Math Cad Program.

III. Technique Of Carrying Out A Rank Analysis

The general research methodology in the field of power consumption and energy saving of an industrial enterprise can be conditionally divided into two levels.

The first level corresponds to studies aimed at specific technical and technological developments that contribute to reducing energy consumption. The methodology here is based on simulation modeling based on the axiomatic Gaussian distributions. This makes it possible to widely use probabilistic convolutions in determining the laws of operation and quasi-parallel algorithms in modeling.

The second level corresponds to the study of energy saving. Here is the optimization of power consumption of an industrial enterprise as a whole. Optimization of power consumption at the second level is carried out in the framework of a related methodology in two stages.

a) At the stage of analyzing the electricity consumption of an industrial enterprise according to specially developed request forms, data are collected on all electricity consumers. This allows one to identify objects that are provided with electricity in violation of existing organizational and technical requirements to prepare a sample of data for further multivariate analysis (energy audit).

b) At the development stage, the information-analytical complex “Power supply of objects belonging to the enterprise” is a developed sample of data on the power consumption of the enterprise’s facilities, including a bank and a data management system, as well as design and graphic modules. The complex can be successfully used in planning and forecasting, and also allows one to quickly track information about consumers of electricity, to update the source data for analysis almost in real time. At the request of the operator, any information on electricity consumers with the necessary level of details and generalization can be obtained from the database (information and analytical complex of the automated system for electricity consumption dispatching control ASECDC). As a methodological basis, it is at this level that rank analysis is widely used, based on the technocenological approach, mathematical statistics, and the theory of hyperbolic infinitely divisible distributions. Given there are fundamental conceptual and methodological differences that underlie the research, it is considered as systematic in relation to the level of research related to specific technical and technological solutions in the field of energy saving. At the stage of statistical analysis and the construction of an empirical model of the process of power consumption, a full-scale statistical processing of data on power consumption is carried out, which includes rank and cluster analysis. Rank analysis allows one to streamline information, to effectively prognosticate the power consumption of individual objects and the enterprise as a whole, to identify in a dynamic way and visually represent objects with abnormal power consumption. Cluster analysis allows one to break objects into groups and rationing the power consumption of objects in each group with a detailed statistical description of the norms.

The rank analysis consists in dividing the technocenosis objects into three groups of ranks: the Noah's, the Pointer, and the locust distribution caste.

Noah's caste is a group of the most energy-intensive objects occupying the first ranks of the rank H distribution and forming the first point of the approximating rank H distribution. The procedure for determining the first caste is formalized by two conditions: 1) a sequence of rank H-distributions is constructed, where in each subsequent distribution the largest object is excluded as long as the objects dropped at the considered time interval coincide in time with the trajectory of the structural-topological dynamics with the first-rank trajectory; 2) in the case of the first condition, if the largest object is excluded, the rank indicator does not change when the rank H distribution is approximated.

An excluded object or a group of the largest objects when two conditions are fulfilled simultaneously and form the first Noah's caste.

Pointer caste is a group of objects connected by a function of cenological influence, a number of which determines the numerical value of the rank indicator β. Pointer caste objects have a high coefficient of concordance; therefore, there is a formalized rule for determining the pointer caste boundaries. The function of the cenological influence on each object of the rank H-distribution is formalized: the probability function of attendance of each rank by various objects on the structural-topological dynamics. The function reflects the strength of competition for a particular rank. When moving from the "head" of the rank H-distribution to the "tail", the degree of cenological influence on the formation of the dynamics of each object on the structural-topological surface increases. The pointer boundary is determined by the rank with the maximum of the cenological influence function.

Locust caste (virtual) - a group of objects beyond the pointer border. This is a group of small objects corresponding to large ranks (the "long tail" of the rank H-distribution) and practically indistinguishable by parameters. In full, the rank analysis includes the following steps:

- allocation of technocenosis;
- determination of the list of modes;
- setting the imaging parameters;
- parametric description of technocenosis;
- construction of tabulated rank distribution;
- construction of graphical rank modes distribution;
- construction of graphical rank parametric distributions;
- construction of mode distribution;
- approximation of distributions;
- optimization of technocenosis.

The algorithm, determining the confidence intervals and prognosis values of power consumption for electrolyzers, as the most energy-intensive process equipment, is given below.

1. According to the electricity meter readings, a sampling $\{W\}$ of power consumption values for the period from 2008 to 2017 was obtained (t = 10 hour), kWh:

$$\{W\} = \begin{bmatrix} 21782207 \\ 17568856 \\ 7884202 \\ 10229538 \\ 11611787 \\ 10926441 \\ 8610614 \\ 11901777 \\ 13314319 \end{bmatrix}. \quad (2)$$

2. The average value $\bar{W}$ is determined, kW·hour:

$$\bar{W} = 1.519 \cdot 10^7 . \quad (3)$$

3. The standard S, kW • hour sampling $\{W\}$ is calculated:

$$S = 4.545 \cdot 10^6 . \quad (4)$$

4. The upper and lower limits of the confidence interval are determined, kW hour:

$$W_{upper} = \bar{W} + t_{st} \cdot \frac{S}{\sqrt{n}}; \quad (5)$$

$$W_{lower} = \bar{W} - t_{st} \cdot \frac{S}{\sqrt{n}} \quad (6)$$

where t_{st} is the value of the Student's criterion at the accepted significance level α=0,05, $t_{st} = 1.96$.

n is the sample size; n = 10 hour.

$W_{upper} = 2.05 \cdot 10^7$ kW·hour; $W_{lower} = 9.861 \cdot 10^6$ kW·hour.

5. The numerical values of the confidence intervals for the main equipment of the castes are determined.

6. The anomalous values of power consumption, beyond the limits of confidence intervals are determined. For further calculations, the $\{W\}$ values for 4 years are excluded. Truncated samples are:

$$\{W\} = \begin{bmatrix} 17568856 \\ 10229538 \\ 11611787 \\ 10926441 \\ 11901777 \\ 13314319 \end{bmatrix}. \quad (7)$$

7. The Mathcad program was used to prognosticate electricity consumption by clusters of Noah's and Pointer castes. The form of the mathematical model (approximating functional) is an exponentially damped harmonic function of the following form:

$$W(t,u) = cos(u_0 t + u_1) e^{u_2 t} + u_3 \quad (8)$$

where t is time, year;

u_0, u_1, u_2, u_3 are constant coefficients obtained using the algorithm.

8. A matrix is drawn up by which the coefficients of the exponential-cosine approximation dependence are determined. The first element of the matrix is the initial function, the other elements are partial derivatives of the determined coefficients. The resulting matrix has the form:

$$F(t,u) = \begin{bmatrix} cos(u_0 t + u_1) e^{u_2 t} + u_3 \\ -sin(u_0 t + u_1) t e^{u_2 t} \\ -sin(u_0 t + u_1) e^{u_2 t} \\ cos(u_0 t + u_1) t e^{u_2 t} \\ 1 \end{bmatrix}. \quad (9)$$

9. The matrix of preliminary values of the coefficients is set:

$$g = \begin{bmatrix} -1 \\ +1 \\ -1 \\ +1 \end{bmatrix}. \quad (10)$$

10. The resulting coefficients are u_0, u_1, u_2, u_3:

$$u = \begin{bmatrix} -1.067 \\ 0.338 \\ -0.515 \\ 1.235 \end{bmatrix}.$$

Determination coefficient is R^2=0,726.

11. For the obtained prognosis model, a retrospective estimate of the relative error of the model was carried out. The following values were taken as comparative values: the actual electricity consumption by the electrolyzer for 2018 (W_{real}) and the forecast ($W_{forecast}$), obtained from model (8).

IV. Results and Discussion

Currently, there is a need to conduct additional research of the higher harmonics and to develop measures to reduce non-sinusoidal voltage at non-ferrous metallurgy enterprises.

For evaluation of the non-sinusoidal voltage in various industries, the systemic techno-cultural approach has recently been applied. This approach is based on the concept of technocenosis, which reflects the specificity of the links between technical elements as individuals. It can be proven that technical systems, such as large industrial enterprises, operate and develop according to the same laws that underlie biological systems (biogeocenoses). To describe the structure of technocenoses and to identify trends in their development and change, a special mathematical apparatus of hyperbolic H-distributions has been developed, having the form: $y=\alpha/r^{\beta}$ (α, β - coefficients, r - rank).

As a result of the cluster analysis and expert assessments, numerical limits have been identified for classifying consumers of electrical energy into the Noah's, pointer and locust distribution castes [5-12].

Figure 3 shows the structure of electrical energy consumption by the main technological equipment of hard alloys production enterprises.

Figure 3 shows that electrolyzers, welding machines and pumps are the most energy-intensive equipment of the plant. They account for about 47% of the total power consumption of the enterprise.

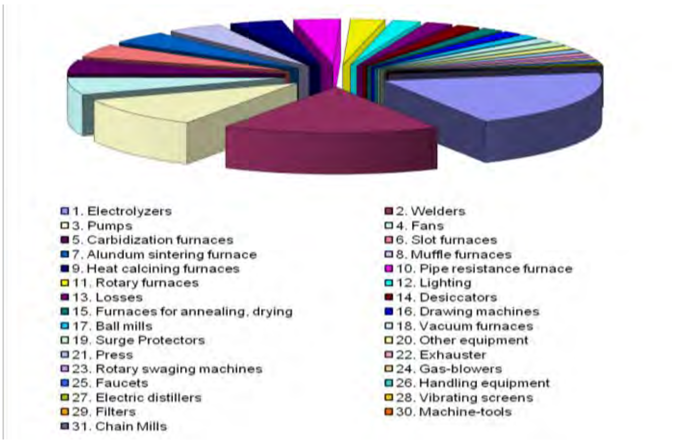

Fig. 3. The structure of electrical energy consumption by the main technological equipment of hard alloys production enterprises.

After the text edit has been completed, the paper is ready for the template. The template file is duplicated by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, we must highlight all of the contents and import our prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

The results of the construction of successive rank *H*-distributions show that the most energy-intensive equipment belongs to the Noah’s caste of distribution (consumers with ranks 1-6).

Similarly, the equipment has been specified constituting the pointer and the locust distribution caste (consumers with grades 7-11 and 12-31 respectively).

In the course of the energy audit, representative samples have been obtained of the average values of the *W* power consumption by consumers of the Noah’s and the pointer distribution castes and the non-sinusoidal coefficients k_U in a percentage relationship.

Figure 4 shows the dependencies of k_U and *W* on the rank of consumers (k_U=*f* (rank), *W*=*f* (rank)) for consumers of Noah’s (rank 1-6) and pointer (rank 7-11) distribution casts.

The least-squares method was applied to obtain the pair correlation coefficients by the expression:

$$r_{k_U,W} = \frac{\sum\left(k_{U_i} - \bar{k}_U\right)\cdot\left(W_i - \bar{W}\right)}{n\cdot\sigma_{k_U}\cdot\sigma_W} \qquad (11)$$

where *n* is the number of measurements; σ_{kU} - the standard deviation of the non-sinusoidal coefficients k_U; σ_W - the standard deviation of the electric power consumption *W*; $\bar{k}_U, \bar{W}$ - average values of non-sinusoidal and power consumption coefficients.

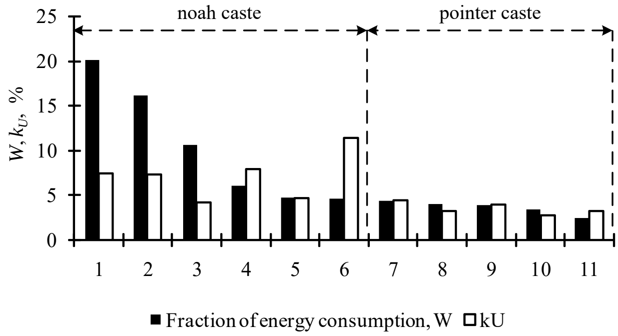

Fig. 4. Dependences W=f(Rang), kU=f(Rang).

The coefficients of pair correlation between the non-sinusoidal voltage coefficient (k_U, %) and the share of the Noah’s and the pointer castes of energy consumers (*W*, %) are 0.56 and 0.37 respectively. The obtained coefficients of pair correlation allow one to estimate the degree of statistical coupling between the two considered parameters varying from -1 to +1.

V. Conclusion

A rank analysis of the Noah’s caste of electric power consumers has been performed, and it has been determined that the values of the coefficients of pair correlation between k_U and the share of Noah’s and pointer castes of electrical energy consumers (*W*, %) for hard-alloy production are 0.56 and 0.37, respectively.

The next stage in the study of electricity quality in power supply systems for industrial enterprises is determination of actual contributions of consumers and the system to the non-sinusoidal voltage. Such contributions are identified on the basis of active experiments; the short-term inclusion of power transformers of substations for parallel operation, in particular.

Acknowledgment

The research on "Research and development of mathematical models of power quality in the non-ferrous metallurgy enterprises" (MK-1324.2007.8) has been supported by the Grant of the President of the Russian Federation for support of young scientists.

References

[1] O.P. Mahela, A.G. Shai, “Power quality improvement in distribution network using DSTATCOM with battery energy storage system,” International Journal of Electrical Power & Energy Systems, vol. 83, December 2016, pp. 229-240.

[1] H. Norouzi, S. Abedi, R. Jamalzadeh, M.G. Rad, S.H. Hosseinian, “Modeling and investigation of harmonic losses in optimal power flow and power system locational marginal pricing, Energy,” vol. 68, 15 April 2014, pp. 140-147.

[2] C. Patrao, J. Delgado, A.T. de Almeida, P. Fonseca, “Power Quality Costs estimation in Portuguese industry,” 11th International Conference on Electrical Power Quality and Utilisation, 17 – 19 October 2011, pp. 1-6.

[3] B.A. Ahmad, H.H. ElSheikh, A. Fadoun, “Review of power quality monitoring systems,” 2015 International Conference on Industrial

Engineering and Operations Management (IEOM), 3-5 March 2015, pp. 1-8.

[4] N.S. Gujar, S.K. Talati, “Power quality monitoring and mitigation,” 2017 7th International Conference on Power Systems (ICPS), 21-23 December 2017, pp. 111-115.

[5] A. Kusko, M. Thompson, “Methods and means of energy quality assurance,” Dodeka-XXI, Moscow, 2010, 336 p.

[6] A.M. Lipsky, “The quality of electricity supply industry,” High School, Kiev, 1985, 160 p.

[7] I.E. Vasiliev, R.V. Klyuev, E.I. Vasiliev, O.A. Kotova, “Research non-sinusoidal voltage to the power supply system of non-ferrous metals,” Math. Universities. Electromechanics, Special edition of "Electricity", 2008, p. 160.

[8] I.I. Bosikov, R.V. Klyuev: System analysis methods for natural and industrial system of mining and metallurgical complex,” Vladikavkaz, IPC IP CopanovaA.Ju. Publ., 2015, 124 p.

[9] O. Boudebbouz, A. Boukadoum, S. Leulmi, “Effective apparent power definition based on sequence components for non-sinusoidal electric power quantities,” Electric Power Systems Research, vol. 117, December 2014, pp. 210-218.

[10] W.G. Morsi, M.E. El-Hawary, “Selection of suitable fuzzy operators for representative power factor evaluation in non-sinusoidal situations,” Electric Power Systems Research, vol. 81, Issue 7, July 2011, pp. 1381-1387.

[11] O.G. Burdzieva, V.B. Zaalishvili, O.G. Beriev, A.S. Kanukov, M.V. Maysuradze, “Mining impact on environment on the North Ossetian territory,” International Journal of GEOMATE, vol. 10(1), 2016, pp. 1693-1697.

[12] V.I. Golik, A.N. Doolin, M.A. Komissarova, R.A. Doolin, “Evaluating the effectiveness of utilization of mining waste,” International Business Management, vol. 9(6), 2015, pp. 1119-1123.