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## Contents



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# Instrumental Research on the Voltage Harmonic Distortion Coefficient in the Modern 110 kV Urban Electric Network

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**Abstract** – *The article deals with assessing the level of voltage non-sinusoidality in the electric network with voltage of 110 - 220 kV. By carrying out direct measurements at a fixed number of connections of urban substations on the high voltage side, the materials were collected for analyzing higher harmonic voltage components. The measurements were carried out in accordance with the requirements of this procedure and with participation of employees of the energy supply company as part of the planned energy audit activities. Based on the results of the analysis, it is stated that the permissible, and in some cases limiting values of the higher harmonic components of the voltage are exceeded. During the analysis, the practice of assessing the harmonic composition in foreign countries, such as the United States of America, was studied, where harmonics were taken into account not only in voltage but also in current. Based on the results obtained, the authors consider that the current standard that regulates the quality of electrical energy in the Republic of Kazakhstan and in the territory of the CIS countries does not fully meet the requirements of the current situation in the electric networks. The reason is the rapid growth of types of electrical receivers based on semiconductors, which is not fully taken into account in the current standard. The authors state the further growth of power receivers with a non-linear consumption characteristic, which will worsen the situation regarding the non-sinusoidal voltage.* 

***Keywords****:* *Non-Sinusoidal Voltage, Additional Energy Losses, Higher Harmonics, Electrical Energy Quality*

## Nomenclature

| | |
|---|---|
| N.p.l. | Normally permissible level |
| M.p.l. | Maximum permissible level |
| A.m.p.l. | Values above the maximum permissible level |
| MES | Ministry of Education and Science |
| SS | State Standards |
| IEEE SA | IEEE Standards Association |
| AEDC JSC | JSC "Akmola Electric Grid Distribution Company" |
| TPPA-1 | Thermal Power Plant-1 in Astana |
| $K_A$ | The sinusoidal distortion coefficient |
| $m_1$, $m_2$, $m_3$ | Number of measurements within one day for N.p.l., M.p.l., A.m.p.l., respectively |
| $N$=1440 | Measurements within one day |

## I. Introduction

Ensuring reliable power supply to consumers is inextricably linked with maintaining the quality of electrical energy. It is obvious that the factors affecting the quality of electricity changing quantitatively and qualitatively over time, which is associated with changing characteristics of energy consumers [1]-[4].

The problem of power quality is considered within the framework of the following main aspects [1]-[8], [21]-[24]: prevention of wear and premature failure of equipment; false alarms of anti-emergency automation; decreasing technical and economic indicators of the equipment operation. Among a lot of aspects of the electrical energy quality, this article is aimed at determining the degree of non-sinusoidal voltage impact on the level of electrical energy losses in the future research. Regarding the issue of maintaining the quality of electrical energy in general in the Republic of Kazakhstan, several significant aspects should be noted:

1. In the territory of the Republic of Kazakhstan, the quality of electricity is normalized by the current standard [9]. As part of implementing this standard, historically, the policy of power supply companies is aimed at controlling the mode of the electric network with respect to voltage deviation, which is considered effective and sufficient. In general, in the material of the article it will be shown that this is currently being carried out, but the situation will obviously worsen further and it is necessary to carry out some studies.

2. This standard [9] was adopted in 1997, when the power supply system was mainly represented by industrial load. The sector of household load grew

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significantly, which changed the composition of consumers and consumption characteristics. In the industrial and domestic sectors, the number of power receivers that consume non-sinusoidal current (non-linear consumers of electrical energy increased. It caused additional losses of electrical energy.. Such receivers are semiconductor power electronics, electric drives with valve converters, electric welding sets, etc.

The described aspects allow drawing intermediate conclusions: it is necessary to revise the normative document regulating the quality indicators of electric energy, taking into account changes in the conditions of electricity supply over the past period; to analyze the practical conditions for monitoring the quality of electricity, in particular, the effect of non-sinusoidal voltage on the technical and economic indicators of the mode of the electric network operation.

The presence of voltage non-sinusoidality causes increasing the magnitude of power losses due to the flow of higher harmonic voltage components. Losses of electricity in the electric networks of Kazakhstan, depending on the voltage class, range from 6 to 18%. The main share of these losses falls on power lines [10] and it is important to determine the share of additional losses from the action of non-sinusoidality.

Currently, power supply companies in the Republic of Kazakhstan do not apply methods of calculating electricity losses, taking into account non-sinusoidal voltage. All additional losses are written off as commercial losses, which are unfairly paid by consumers. The tariff policy also cannot clarify, because there is no clear understanding of the non-sinusoidal voltage effect and its accounting.

To visualize the ongoing processes in the electric network under current conditions, it is necessary to analyze in detail the effect of non-sinusoidal voltage on power losses. To do this, it is necessary at the first stage to carry out studies of the non-sinusoidal voltage presence in the electric network and to consider its main sources.

It was noted above that the main sources of non-sinusoidal voltage are power receivers with non-linear consumption characteristics. The sources of non-sinusoidal voltage are also such elements of power supply systems as power transformers [2], [11]-[14] and power lines [15]. In the process of saturation of the transformer core, there occur harmonics that are multiples of three. The saturable core inductor resistance depends on the amplitude of the flowing current, which causes distortion of the current curve. This occurs in underloaded transformers operating under increased voltage.

The air lines in the territory of the Republic of Kazakhstan have a significant length. In long lines, resonant modes are observed, the causes of which are associated with capacitance of the wires relative to the ground and to each other and self-inductance of the overhead line. Depending on the length and loading of the line at certain frequencies, capacitance and inductance cause resonant modes, which causes the occurrence of currents and voltages at these frequencies.

Thus, non-linearity of the transformer magnetization characteristics and the frequency characteristics of long lines also affect the harmonic composition of currents and voltages in the electric network.

It should be added that the current trend towards digitalization causes a higher degree of automation of technological processes, which will also aggravate the non-sinusoidal voltage in the electrical network, since it is based on the use of power semiconductor electronics [2].

Of course, retaliatory measures are being taken to compensate for the negative impact of non-linear consumers of electrical energy through the use of filter-compensating devices [16]-[19]. They, when properly adjusted, filter out higher harmonics. It should be noted that this is fully effective for large industrial enterprises but not for power supply systems for household loads.

Summarizing all the above, one comes to the understanding that identification of the level of electricity losses from the flow of higher harmonic voltage components and its assessment will lead to reducing losses in the electric networks, and will also contribute to the full implementing of the energy saving and energy efficiency policy in the current conditions and in the future.

In addition, the results of the study show that it will be necessary to revise and to supplement the regulatory documents related to the indicators of the electrical energy quality. It should also be noted that a natural consequence of reducing excess electricity losses will be a slowdown in the growth of electricity tariffs.

To identify, to substantiate and to put into practice the expected potential, it is necessary to monitor and to analyze the structure of losses, taking into account the influencing factors. These goals are fulfilled within the framework of the grant project (This work was supported by the MES of the Republic of Kazakhstan, grant No. AP09058186) energy at 10 substations located within the city of Astana to analyze the current situation and to develop recommendations. Instrumental studies of the mode parameters were carried out on the high voltage side of 220 (110)/10(6) kV substations. The measurements were carried out at 20 connections outgoing from the substations.

The analysis of higher harmonics in electrical network nodes is further conducted, and instances of their values exceeding permissible limits are established. It is demonstrated that the current values of higher harmonics do not fully comply with the requirements of the regulatory document.

## II. Research Methods

The electrical energy quality indicators were measured by the Fluke 435-II instrument (Figures 1(a)-(c)) in accordance with SS 13109-97 Electrical energy. Compatibility of technical means is electromagnetic.

(a)

(b)

(c)

Figs. 1. Taking measurements of indicators of the electrical energy quality

Standards for the quality of electrical energy were determined in general-purpose power supply systems. Based on the data obtained, an assessment was made of indicators of the electricity quality.

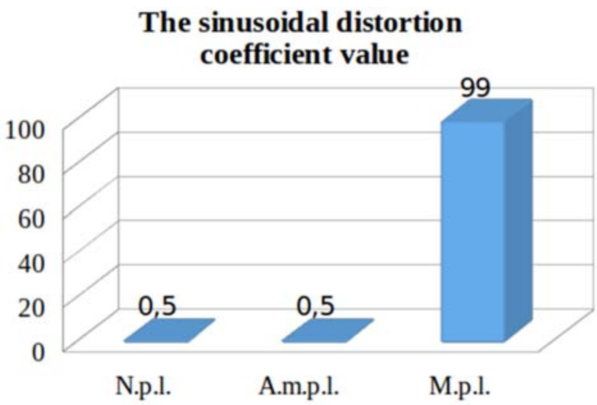
From SS 13109-97, the following were selected to assess the quality of electricity:

- the coefficient of distortion of the voltage curve sinusoidality;
- the coefficient of the voltage *n*-th harmonic component;
- the coefficient of asymmetry in reverse sequence.

For a full assessment, the numerical values of these indicators were divided into three groups: normally acceptable; maximum permissible; values above the maximum permissible, if any. During measurements, the minimum period was 24 hours, which corresponds to SS 13109-97. The frequency of measurements was one measurement per minute, $N$=1440 measurements within one day, respectively. When measuring the values of the harmonic components, the numerical series up to the 50th was taken into account. When analyzing connections, the greatest interest was paid to finding places with the worst indicators of power quality. All the measurements of power quality indicators were divided into the above groups. Processing the obtained data in this way allows confirming the thesis about the widespread violation of some indicators of the electricity quality relative to the normal levels.

## III. Research Results

For an example of the above analysis, Figure 2 shows the distortion factor distribution of the sinusoidal voltage in the network with voltage of 110 kV of AEDC JSC at the Shkolnaya substation. Among all the objects selected for study, the worst situation is observed as regarding the sinusoidal distortion coefficient Of all the objects selected for study, the worst situation is observed here regarding the sinusoidal distortion coefficient (Figure 3), which is found by the formula: $K_A = \sqrt{\sum_{i=1}^{n} K_{Ai}^2}$. But it will be shown below that, taking into account this indicator alone is not sufficient. So, in particular, at many substations, the value of the sinusoidal distortion factor is within the limits of SS 13109-97, but a detailed picture of the harmonic components of the voltage indicates significant deviations from the norms given in the standard.




N.p.l.– normally permissible level, M.p.l. – Maximum permissible level, A.m.p.l. – Values above the maximum permissible level.

Fig. 2. Distribution of voltage distortion coefficient on the Shkolnaya- TPPA-1 line

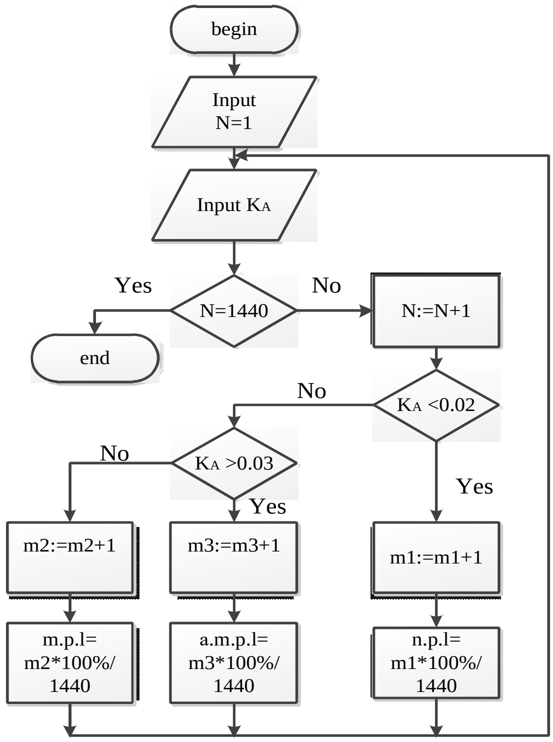



Fig. 3. The calculation algorithm for Table I

The most complete picture of the harmonic voltage components distribution in the overall structure is shown in Table I and Figure 4.

Analyzing the information given in Figure 1, it can be seen that some of the values of the voltage distortion coefficient do not meet the requirements of normally permissible level, although according to the standard, compliance should be at least 95 percent. The maximum permissible value is 99 percent, although it should be less than 5 percent, and 0.5 percent in fact goes beyond the maximum permissible level.

TABLE I
VOLTAGE HARMONIC COMPOSITION DISTRIBUTION AT SUBSTATIONS

| Substation | Number of studied connections / voltage level | Distortion coefficient values | | |
|---|---|---|---|---|
| | | N.p.l., % | M.p.l., % | Values A.m.p.l., % |
| Airport | 3 / 110 kV | 100 | 0 | 0 |
| | | 100 | 0 | 0 |
| | | 100 | 0 | 0 |
| Batys | 3 / 220 kV / 110 kV | 0 | 100 | 0 |
| | | 12 | 88 | 0 |
| | | 100 | 0 | 0 |
| Dostyk | 1 / 110 kV | 100 | 0 | 0 |
| Zhuldyz | 2 / 110 kV | 100 | 0 | 0 |
| | | 100 | 0 | 0 |
| Zarechnaya | 2 / 110 kV | 99 | 1 | 0 |
| | | 99 | 1 | 0 |
| Karaotkel | 1 / 110 kV | 93 | 7 | 0 |
| PNF | 2 / 110 kV | 6 | 94 | 0 |
| | | 15 | 85 | 0 |
| Turan | 2 / 110 kV | 100 | 0 | 0 |
| | | 100 | 0 | 0 |
| Chubary | 2 / 110 kV | 100 | 0 | 0 |
| | | 100 | 0 | 0 |
| Shkolnaya | 2 / 110 kV | 0.5 | 99 | 0.5 |
| | | 56 | 44 | 0 |

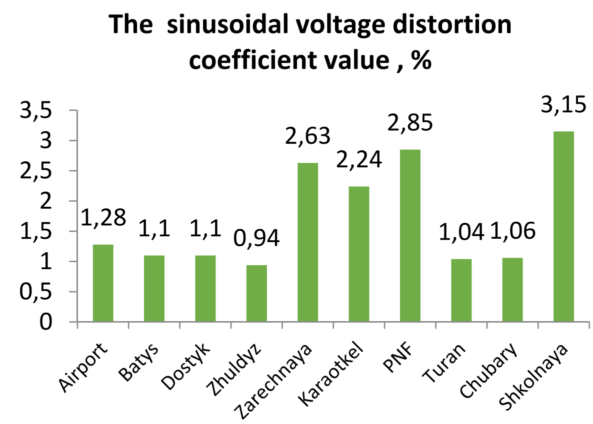



Fig. 4. The voltage distortion coefficient values at substations

The values recorded in Table I in the columns of the harmonic distortion factor values are obtained by processing the measured data, and they correspond to cases of exceeding the standard levels failing to meet the SS.

For sure, the attained results do not declare total violations, but given the trends and the current state of the development of the power consumption market with further automation and digitalization, it is still necessary to recognize higher voltage harmonics as a source of extra electrical energy losses during its transit through high voltage grids.

As part of the ongoing survey, the authors aim at the final outcome as the improved models for calculating electrical energy losses, given the possibility of assessing the scale of additional losses in high voltage electrical grids caused by non-sinusoidality and asymmetry of currents and voltages and the elaboration of mechanisms for its reduction in the near future.

To complete the picture of the state of the described issue, the authors of the article presented a diagram of the harmonic voltage components distribution in Figure 5.

The analysis of the harmonic composition states not just the excess of normally permissible levels, in this case the 5th harmonic, but also the excess of numerical values outside the maximum permissible values (harmonic numbers – 4 and 5), this clearly shows the emergence of dangerous trends in the future, in relation to the conditions for the economical operation of power supply systems and the adequacy of the content of regulatory documents governing this area.

For consideration, Table II presents the data of the harmonic components for which the maximum allowable level is exceeded, the harmonic series is taken up to the 10th harmonic. The full range in the study included up to 50 harmonics.

Table II shows that the situation, in terms of harmonic components is in general as follows: the 2nd, 3rd, 4th, 5th, 7th, 9th, 10th harmonics go beyond the maximum permissible levels regulated by the standard. This provision requires the adoption of measures for a detailed study and changes in operational practice.

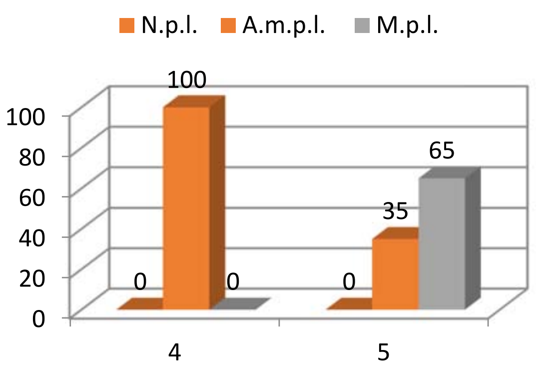



Fig. 5. Diagram of the harmonic voltage components distribution on the Shkolnaya TPPA-1 line

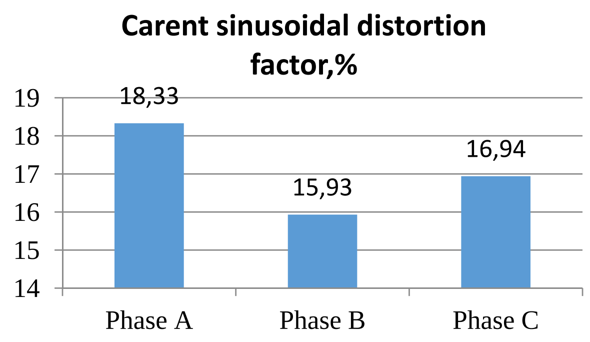



Fig. 6. Absolute values of the current sinusoidal distortion coefficient on the Airport-Northern line

TABLE II
HARMONIC COMPONENTS FOR WHICH THE MAXIMUM PERMISSIBLE LEVEL IS EXCEEDED

| **Substation** | Line | Number of the voltage harmonic component | Indicator that are beyond the limits of the maximum permissible level, % |
|---|---|---|---|
| Airport | 1 | 4 | 98 |
| | 1 | 10 | 12 |
| | 2 | 4 | 64 |
| | 3 | 4 | 100 |
| | 3 | 10 | 15 |
| Batys | 1 | 3 | 99 |
| | 1 | 7 | 7 |
| | 1 | 9 | 7 |
| | 2 | 3 | 96 |
| | 3 | 2 | 10 |
| Dostyk | 1 | 4 | 86 |
| Zhuldyz | 1 | 4 | 97 |
| | 2 | 4 | 96 |
| Zarechnaya | 1 | 4 | 96 |
| | 2 | 4 | 95 |
| Karaotkel | 1 | 3 | 99 |
| PNF | 1 | 3 | 100 |
| | 2 | 3 | 100 |
| Turan | 1 | 4 | 93 |
| | 2 | 4 | 92 |
| Shkolnaya | 1 | 4 | 100 |
| | 1 | 5 | 35 |
| | 2 | 4 | 100 |
| | 2 | 5 | 8 |

As a possible measure, a correction of the content of the current SS 13109-97 is proposed.

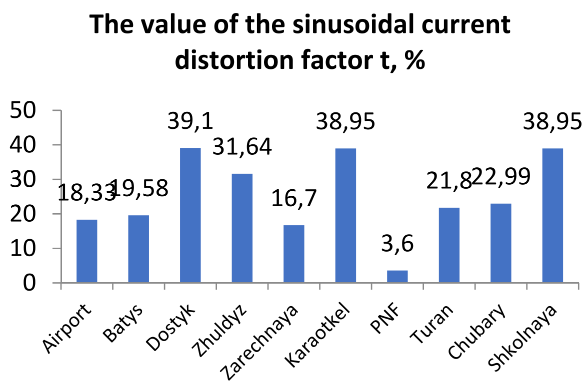



Fig. 7. Current distortion coefficient values at substations

The grounds are the results of the authors' own research, a review of documentation regarding the quality of electricity, among which the publication of specialists from the United States of America seems to be especially useful [20]. The authors of the article (T.M. Blooming and D.J. Carnovale) analyze the practical application of the standard "IEEE SA 519 - 1992 Recommended Practices and Requirements of the Institute of Electrical and Electronics Engineers for Harmonics Control in Electric Power Systems" that deals with the practice of assessing the quality of electrical energy, namely regarding harmonic components. So, in particular, in the American standard, the limits of harmonics change are monitored not only in voltage but also in current.

Moreover, the value of current harmonics depends on the value of the ratio of the short-circuit current to the load current at the measurement site; in general, this takes into account the electrical distance from the generation units. For example, Figure 6 shows the data of absolute values of the sinusoidal current distortion factor at one of the substations in the city of Astana. Under the absolute values, the maximum values in the phases during the measurement time are given. A similar picture is observed on more than half of the studied substation lines. A complete picture of the distortion coefficient of the sinusoidal current is shown in Figure 7. The absolute values are the maximum values in phases during the measurement. A similar pattern is observed on more than half of the surveyed substation lines.

Summarizing the results of the own research and the conclusions of a specific example of foreign authors, the authors have to admit that the further development of power supply systems requires taking into account higher current harmonics in order to fully take into account the effect of non-linear consumers and their negative consequences. In continuation, it will be necessary to correct the current models for calculating the losses of electrical energy, taking into account the effect of non-sinusoidal voltage and asymmetry.

## IV. Conclusion

The stable operation of modern urban power supply systems requires careful attention to power quality indicators, in particular to non-sinusoidality, which can reach unacceptable maximum permissible levels, and in some cases even exceed the maximum permissible levels allowed by the standard. Violation of power quality indicators leads to violation of economical modes and can lead to emergency situations. This is especially important, since the electrical networks of large cities in the Republic of Kazakhstan are being intensively built and saturated with regulated electrical receivers, which increasingly worsen the non-sinusoidality of the supply voltage. To form an objective picture of the ongoing changes in the current SS 13109-97, it is necessary to take into account the coefficient of non-sinusoidality not only in voltage but also in current, as it was done in the USA.

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# *International Journal on Energy Conversion (IRECON)*

## Aims and scope

The ***International Journal on Energy Conversion (IRECON)*** is a peer-reviewed journal that publishes original theoretical and applied papers on all aspects regarding energy conversion. It is intended to be a cross disciplinary and internationally journal aimed at disseminating results of research on energy conversion. The topics to be covered include but are not limited to:
*generation of electrical energy for general industrial, commercial, public, and domestic consumption and electromechanical energy conversion for the use of electrical energy, renewable energy conversion, thermoelectricity, thermionic, photoelectric, thermal-photovoltaic, magneto-hydrodynamic, chemical, Brayton, Diesel, Rankine and combined cycles, and Stirling engines, hydrogen and other advanced fuel cells, all sources forms and storage and uses and all conversion phenomena of energy, static or dynamic conversion systems and processes and energy storage (for example solar, nuclear, fossil, geothermal, wind, hydro, and biomass, process heat, electrolysis, heating and cooling, electrical, mechanical and thermal storage units), energy efficiency and management, sustainable energy, heat pipes and capillary pumped loops, thermal management of spacecraft, space and terrestrial power systems, hydrogen production and storage, nuclear power, single and combined cycles, miniaturized energy conversion and power systems, fuel cells and advanced batteries, industrial, civil, automotive, airspace and naval applications on energy conversion.*

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