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Methology of experimental research of voltage quality in electrical circuit

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Abstract. This study investigates the causes of electricity quality deterioration and proposes measures to mitigate it. The analysis focuses on the technical conditions for connecting consumers to the electricity network and the necessary conditions for electricity supply. It is recognized that, in addition to quality indicators, auxiliary parameters describing energy quality in terms of current and voltage must be measured. The study presents a graphical approach to analyzing measurement results, comparing load control graphs with energy quality indicator graphs over a 30-minute time interval. The results consider not only compliance with regulatory requirements but also the fulfillment of obligations to ensure electricity quality.

1 Introduction

Control of the quality of electricity is necessary to analyze the causes of breakdowns, identify factors that reduce the quality of electricity, control the quality of electricity, which is necessary for checking the fulfillment of technical conditions for connecting the consumer to the electricity network and the terms of the contract for electricity supply [1-3-4]. It is known that in such cases, in addition to power quality indicators, it is necessary to measure auxiliary parameters that describe power quality in terms of current and power [5-6-7]. At the same time, it is more convenient to see the measurement results not only numerically, but also graphically. To build graphs, parameters are measured in time intervals from 1 to 30 minutes [8-13-14]. The width of the interval depends on the characteristics of the technological process. According to the results of the analysis, not only the compliance of the electricity quality indicators with the regulatory requirements, but also the fulfillment of the contractual obligations of the parties to ensure the quality of the electricity is checked [2-9].

In order to evaluate the quality indicator of electricity in continuously operating power supply networks, it is possible to compare the values obtained using the energy quality analyzer. In our case, the Fluke analyzer, a portable device - Fluke 435 series, is used to determine the quality of electric power for measuring network parameters. [10-11-15].

The electric energy analyzer is made by connecting special conductors of separate current sensors for each phase and neutral to the alternating current network. According to it, the device has 10 measurement channels (4 for current and 6 for voltage), through which all the

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necessary information is obtained. Current sensors with a nominal value of one to a thousand amperes are served by flexible rings [12-16].

2 Materials and methods

The analyzer measures the following network parameters every 30 minutes at two control points within 24 hours: voltage; current; active and reactive (capacitance and inductance) capacities; active and reactive (capacitance and inductance) energy; $\cos\varphi$ for each phase. 3-phase power factor; noted network frequencies. A number of parameters were recorded separately for each phase and summed over all phases. In addition to the current values, the maximum and minimum values of the parameters were recorded for each phase as well as for the total. The spectral composition of current and voltage harmonics is determined up to the 40 th harmonic; deviations and voltage drops were recorded [17].

The device displays the parameters calculated in real time on the display, and they are stored in the device's memory for later playback and analysis.

The Fluke 435 series analyzer processes the analog voltage (current) signal discretely, but at a high frequency. Thus, in one period of the main frequency (0.02 s), 256 measurements are made using an analog-to-digital converter. This makes it possible to determine the effective value of the harmonic components of the 40th level input voltage with a frequency of 2 kHz with the required accuracy. The duration of this interval is equal to 8-16 cycles of the main frequency or 0.16-0.32 s and determines the time called "measurement window". The quality indicator value of this or that electric power is calculated as the average square value of several N_i measurements. This value can be called a calculation that is taken into account in the statistical processing of continuous measurements for 24 hours and is determined according to the following formula.

$$\Pi_U = \sqrt{\frac{\Sigma \Pi_{Ui}^2}{N}} \tag{1}$$

The number *N* with the smallest integer value is determined by the average time interval T_{vs} for the following values:

- voltage deviation N> 18, = 60 s;
- frequency deviation N> 15, = 20 s;
- the distortion coefficient of the sinusoidality of the voltage curve and the i-harmonic component of this voltage N> 9, T_{vs} = 3 s;
- reverse and zero sequence voltage unbalance factor N> 9, T_{vs} = 3 s.

In this case, the number of continuous measurements for 24 hours is as follows: 1440 for voltage deviation, 4320 for frequency deviation, and 28800 for the quality indicator of the remaining electricity, forming a reliable sample for statistical processing of the measurement results.

Phase and phase-to-phase voltage deviations, as well as unbalance factors, are calculated from the main frequency voltage. In the Fluke 435 series analyzer, this requirement is implemented as follows. The input digitized voltage is represented by the Fourier spectrum of the product of the fundamental harmonic frequency. Based on the voltage of the main frequency thus separated, by the method of symmetrical constituents, if the measurements are made in a three-phase network, the voltages of the direct, reverse and zero sequence are calculated. This is the deviation of the voltage in the three-phase network and its asymmetry with respect to the main frequency and the voltage of the correct sequence. The change in voltage deviation in a single-phase network is related to the main frequency voltage. As a result, the values of the quality indicator of electricity in each average interval and the damages caused by low-quality electricity are determined as follows [18-20].

For voltage deviation:

- The average value of the fundamental frequency for $N \geq 18$ in the interval of 60 s and the values of the correct sequence voltage $U_{1(1)i}$, V:

$$U_y = \sqrt{\frac{\Sigma_{i=1}^{N} U_{1(1)i}^2}{N}} \tag{2}$$

where $U_{1(1)i}$ - is the main frequency and the phase (phase-to-phase) voltage of the correct sequence.

- voltage deviation δU, %:

$$\delta U_y = \frac{U_y - U_{nom}}{U_{nom}} \cdot 100 \tag{3}$$

To deviate from the frequency:

- an interval of 20 s by N> 15 to the i-th measurements of the average value of the main frequency Δt_{fi} in the duration of 8 periods so that the average frequency value is $f_i = \frac{1}{\Delta t_{fi}}$ Hz average value in:

$$f_y = \frac{\sum_{i=1}^{N} f_i}{N} \tag{4}$$

Frequency deviation Hz, $\Delta f = f_y - f_{nom}$

For the coefficient of the n-harmonic component of the voltage:

- i-th average values in 3 s interval for N> 9 , %:

$$K_{U(n)} = \sqrt{\frac{\sum_{i=1}^{N} K_{U(n)i}^2}{N}} \tag{5}$$

here $K_{U(n)i} = \frac{U_{(n)i}}{U_{(1)i}} \cdot 100$, $K_{U(n)} \cdot 100\%$ I s the i-th voltage value and, the value of the nth harmonic and the first (fundamental) harmonic V, respectively.

For the distortion coefficient of sinusoidal voltage:

- Average i-th values at 3 s intervals for N> 9, %:

$$K_U = \sqrt{\frac{\sum_{i=1}^{N} K_{Ui}^2}{N}} \tag{6}$$

where $K_{Ui} = \sqrt{\frac{\sum_{i=2}^{N\ 40} U_{(n)i}^2}{U_{(1)i}}}$ - K_{Ui} the i - th value of

For the nonsymmetry coefficient in the reverse (zero) sequence:
i - th averaged value

$$K_{2Ui} = \frac{U_{2(1)i}}{U_{1(1)i}} \cdot 100\%, \qquad K_{0Ui} = \frac{U_{0(1)i}}{U_{1(1)i}} \cdot 100\%, \tag{7}$$

N> 9 average i - th value in the interval of 3 s

$$K_{2U} = \sqrt{\frac{\sum_{i=1}^{N} K_{2Ui}^2}{N}} \qquad K_{0U} = \sqrt{\frac{\sum_{i=1}^{N} K_{0Ui}^2}{N}} \tag{8}$$

Statistical processing of measurement results is the basis for presenting the quality indicator of electricity in the form of graphs.

Graphs of voltages and currents in terms of harmonics affecting the quality of electricity at the distribution point (Figure1, Figure 2.)

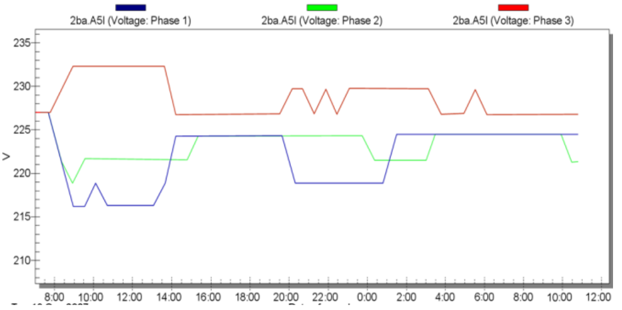

Fig. 1. Distribution point voltage graphs.

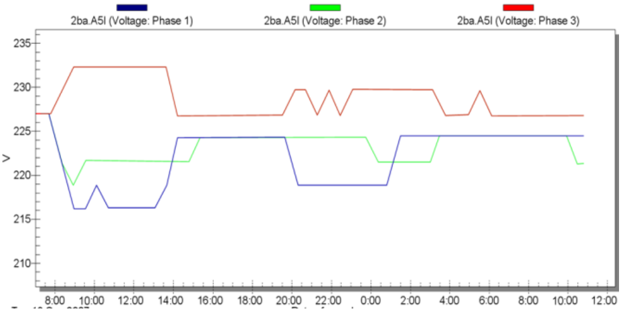

Fig. 2. Distribution point current graphs.

In electric machines, losses due to high harmonics and voltage unsymmetry belong to the main losses, which form a collection of losses from the main power flow of copper conductors and active steel, as well as mechanical losses. In the presence of higher harmonics of the current in the stator winding of the synchronous machine $\Delta P_{(n)st}$, the losses are determined as follows:

$$\Delta P_{(n)st} = \Delta P_{nom}\left(1+\frac{1}{K_{r1}}\sum_{n} K_{I(n)}^{2} K_{r(n)}\right), \tag{9}$$

where ΔP_{nom} is the losses in the copper coil through which the sinusoidal current flows; $K_{I(n)}$ - harmonic current coefficient; K_{r1} and $K_{r(n)}$ are coefficients of multiplication of losses for the 1st and harmonics of the current determined by the design of the machine. In the phases of the stator windings of the n-harmonic current, a pulsating magnetic driving force is formed, which leads to the appearance of asynchronous magnetic fields in the space, which causes additional losses in the rotor.

Also in synchronous motors, additional losses caused by high harmonics $\Delta P_{\Sigma h.h.}$ are equal to:

$$\Delta P_{\Sigma h.h.} = \sum_{2}^{n} P_{C(n)} + \sum_{2}^{n} P_{st(n)} + \sum_{2}^{n} \Delta P_{b(n)} \tag{10}$$

where $\Delta P_{c(n)}$ is additional waste in the copper tube; $\Delta P_{st(n)}$ - additional losses in steel; $\Delta P_{b(n)}$ is the power required to overcome the braking torque.

Additional losses in copper are determined as follows:

$$\sum_{2}^{n}\Delta P_{c(n)} = k_L^2 \Delta P_{e.sh}\sum_{n}\left(\frac{U(n)}{U_{nom}}\right)^2 \frac{\sqrt{n} + k^{'}\sqrt{n \pm 1}}{n^2} \tag{11}$$

where k_L is the starting current multiple; $\Delta P_{e.sh}$ - losses in short circuit; U_n - effective value of n-harmonic voltage; $k' = \frac{R_2'}{R_1}$ is the equivalent ratio of rotor resistance to stator resistance.

Additional waste in steel is determined as follows:

$$\sum_{2}^{n}\Delta P_{st(n)} = \Delta P_{st.nom}\sum\nolimits_{n}\left(\frac{U_{(n)}}{U_{nom}}\right)^2 \frac{1}{n^{0,7}} \tag{12}$$

where $\Delta P_{st.nom}$ is the nominal losses in the engine steel at the nominal value of the voltage U_{nom}.

Power to overcome braking torque

$$\sum_{2}^{n}\Delta P_{b(n)} = P_{nom}\sum\nolimits_{n}\left(\frac{U_{(n)}}{U_{nom}}\right)^2 \frac{M_L}{M_{nom}}\frac{1}{n^2\sqrt{n \pm 1}} \tag{13}$$

where M_L and M_{nom} are the initial and nominal torques of the synchronous motor.

All the necessary values for calculating additional losses according to the formula (10) - (13) are determined by passport or reference data for a certain type of equipment. $U_{(n)}$ values can be measured with high accuracy in different operating modes of the electric machine.

Additional losses from higher harmonics $\Delta P_{a(n)}$ in synchronous motors ΔP_{nom} specified in the passport, evaluation of the data of the curves formed by the ratio of the nominal losses in the electric motor to the losses at a voltage equal to 1% of the total frequency refer to the literature is carried out according to [19].

The total loss of $\Delta P_{\sum h.h.}$ in a synchronous motor from all high-voltage harmonics is found by the following formula:

$$\Delta P_{\Sigma h.h} = \sum_{2}^{n}\Delta P_{a(n)} = \left(\frac{U_{(n)}}{U_1}\right) \tag{14}$$

In an asynchronous motor, the additional losses due to the *n*-harmonic current are equal to:

$$\Delta P_{a(n)} = 3I_n^2\left(R_{st(n)} + R'_{rot(n)}\right) \tag{15}$$

where $R_{st(n)}$ and $R'_{rot(n)}$ are the active resistance of the stator and the active resistance of the rotor at the nth harmonic frequency, respectively.

The phenomenon of the surface effect occurring at high frequencies is accounted for by the following formulas: $R_{st(n)} = R_{st}\sqrt{n}, \quad R'_{rot(n)} = R'_{rot} = \sqrt{n \pm 1},$ «+» - for high harmonics of the right sequence, «-»- for high harmonics of the reverse sequence. When calculating losses in high-voltage asynchronous motors, $R_{st} = R'_{rot}$ can be accepted.

If we express the current I_n in terms of the rated current of the electric motor and the starting current k_L, the calculation formula for determining the total losses from higher harmonics can be expressed as follows:

$$\Delta P_{\sum h.h.} = \Delta P_{st.nom}k_L\sum_{2}^{n}\left(\frac{U_{(n)}}{U_1}\right)^2\left(\sqrt{n} + \sqrt{n \pm 1}\right) = \Delta P_{st.nom}\sum_{2}^{n}k_{a(n)} \tag{16}$$

where $\Delta P_{st.nom}$ is the nominal copper loss of the stator; $k_{ad(n)}$ - is the coefficient of increase of losses in copper from the *n*-th harmonic.

Additional power losses depending on nominal power in asynchronous and synchronous machines in voltage nosymmetry can be determined according:

$$\Delta P_{*ad.em} = k_{ad.em} K_2^2 U \tag{17}$$

where $k_{ad.em}$ is the coefficient depending on the type of electric machine and takes the following values: for asynchronous motors - 4.5; for turbine generators - 1.86; for hydrogen generators and synchronous motors - 0.68; for synchronous compensators - 1.5.

Additional losses in capacitor banks and filter compensating devices are associated with the occurrence of ferroresonance phenomena, which can lead to overloading of network elements and even failure of electrical equipment [20].

Non-sinusoidal voltage in the clamps of capacitor batteries causes additional active losses due to high harmonics in the dielectric, which are found according to the following formula:

$$\Delta P_{\Sigma die} = \omega \sum_{(n)}^{2} U_{(n)}^2 tg\delta_{nom} C \tag{18}$$

where ω is the nominal angular frequency; U_n - the voltage of the nth harmonic; C - battery capacity; $tg\,\delta_{nom}$ - angular coefficient of dielectric dissipation in the n- harmonic.

According to the studied literature, the value of $tg\,\delta_{nom}$ at frequencies up to 1000 Hz can be taken equal to the nominal value for this type of dielectric. In the frequency range from 1000 to 3000 Hz, the value of $tg\,\delta_{nom}$ increases by about 1.5 times.

Capacitance of the capacitor at frequencies up to 3000 Hz can be taken as $C_n = C_{nom} = C_{const}$. As a result of these assumptions, we have the following formula for determining dielectric losses:

$$\Delta P_{\Sigma die} = U_{nom}^2 \omega C_{nom} tg\delta_{nom} \left(\sum_{n=1}^{20} K_{(n)}^2 n + 1{,}5 \sum_{n=21}^{40} U_{(n)}^2 n \right) \tag{19}$$

and

$$\Delta P_{\Sigma die} = U_{nom}^2 \omega C_{nom} tg\delta_{nom} \left(\sum_{n=1}^{20} K_{U(n)}^2 n + 1{,}5 \sum_{n=21}^{40} K_{U(n)}^2 n \right) \tag{20}$$

where $\Delta U_{nom}^2, \omega C_{nom} tg\,\delta_{nom}$ – is the nominal dissipation of the main harmonic component of the voltage in the dielectric.

Losses in reactors are determined according to the appropriate formula in the literature :

$$\Delta P_{\Sigma M} = 3 \sum_{1}^{n} I_{(n)}^2 r_1 k_{r(n)}, \tag{21}$$

where I_n - is the current of the nth harmonic in the reactor; r_1 - active resistance at the main frequency; $k_{r(n)}$ -is the coefficient of change of active resistance at the frequency of the n-harmonic.

3 Results and discussion

The losses in the LC filter are the sum of the losses in the reactor and the losses in the capacitor banks and the 1st harmonic at the frequencies of the harmonics to which the filter is tuned. According to it, the waste of other higher harmonics entering the filter can be ignored according to the cited literature.

It should be noted that in the presence of capacitor batteries, the reduction of active losses in the network occurs due to the compensation of reactive power. In some cases, the losses in capacitor banks can exceed the losses caused by higher harmonics in the network without them. It can be seen that the use of capacitor banks leads to an increase in total losses. The ratio of losses in the network at the frequency of the nth harmonic $\Delta P_{(n)c}$ in the absence of capacitor banks and losses in capacitor banks $\frac{\Delta P_{(n)SCE}}{\Delta P_{(n)c}} = \frac{1}{k_p nkq_{rp}}$ Here $k_p \frac{Q_{nomCB}}{S_{sh.c}}$, Q_{nomCB} nominal capacity of capacitor batteries; $S_{sh.c}$ - short-circuit power in the node block of the capacitor batteries; $k = \frac{r}{x}$ ratios of active and reactive resistances of the network; q_{rp} - the level of the quality indicator of electric energy. $k_p = (0{,}254 - 0{,}5)\cdot 10^{-2}$ when $k = 0{,}3$ and $q_{rp} = 10$ for $n =$ 5, 7, 13:

$$\Delta P_{(n)SCE} \big/ \Delta P_{(n)C} \approx 1 \div 3 \tag{22}$$

This ratio $\Delta P_{(n)SCE} < \Delta P_{(n)C}$ is high only in capacitor batteries with very large power $k_p > 10^{-2}$ and high-quality filtering circuits, as well as in the absence of capacitor batteries the frequencies of harmonics are realized by the ferroresonance increase of the voltage in the network.

With a non-sinusoidal voltage, additional losses in the transformer due to high harmonics of the currents are determined according to the formula according to the studied literature.

$$\Delta P_{\Sigma.h.t} = 3\sum_{1}^{n} I_{(n)}^2 r_1 k_{r(n)}, \tag{23}$$

where I_n - is the current of the *n*-harmonic; r_1 - the active resistance of the transformer at the main frequency; $k_{r(n)}$ - is the coefficient of change of the active resistance of the current-carrying parts at the frequency of the *n*-harmonic.

Additional losses from higher harmonics of currents in power transmission lines are determined according to the cited literature. In such cases, the coefficient of variation of the active resistance of the current-carrying parts at the frequency of the *n*-harmonic

$$k_{r(n)} = \sqrt{n} \tag{24}$$

The influence of the frequency of high harmonics on the active and reactive resistance of conductors of the AS and ASO brands, as well as 6-35 kV voltage cables of various sections P.I. Experimentally studied in the works of Semichevsky. The active resistance of conductors at the frequency of the n-harmonic was determined as follows

$$r_{0(n)} = r_0 (K_s + K_{cl}), \tag{25}$$

where r_0 -is the constant resistance of the conductor (taking into account the temperature); K_s - the coefficient taking into account the phenomenon of surface effect ($K_s = 0{,}021\sqrt{f}$ - for copper, $K_s = 0{,}01635\sqrt{f}$ - for aluminium); the coefficient K_{cl} takes into account the effect of the proximity of the conductors in the electrical conductor

$$K_{cl} = \frac{1{,}18 + K_s}{K_s + 0{,}27}\left(\frac{d}{a}\right)^2, \tag{26}$$

where d is the diameter of the conductor wire, mm; *a* - the distance between the centers of the wire, mm.

As a result, if there are strong sources of current harmonics in the network, it is desirable to use wires with less surface effect. As for the proximity effect, it should be taken into account for cable lines. For overhead lines, if $a > 50$ mm, the convergence effect is not taken into account.

The origin of additional power wastes in Transformers due to the symmetry of currents and voltages is determined as follows:

$$\Delta P_{t.ad} = \left(\frac{U_2}{U_{nom}}\right)^2 \Delta P_i + \left(\frac{I_2}{I_{nom}}\right)^2 \Delta P_{sh.c} \tag{27}$$

where U_{nom} and I_{nom} are nominal voltage and current by the high voltage of the transformer; U_2 and I_2 - voltage and current of the reverse sequence; ΔP_i and $\Delta P_{sh.c}$ losses of the transformer in normal operation and short-circuit mode. Considering $I_{nom} = \frac{U_{sh.c}}{\sqrt{3} z_{sh.c}}$ reverse sequence current $I_{nom} = \frac{U_2}{\sqrt{3}(z_{sh.c} + z_{L.2})}$ where $U_{sh.c}$ and $z_{sh.c}$ voltage and short-circuit resistance of the transformer; $z_{L.2}$ - reverse series resistance of the load connected to the transformer.

4 Conclusion

From the research carried out in this chapter, it can be concluded that a method of collecting static data on real loads and electricity consumption in electrical networks of technological groups from the description of uninterruptible consumers has been developed.

Graphs of continuous operating loads with a descriptive continuous technological cycle of melting and casting of precious metals were created, which allowed for the first time to determine the main indicators of these graphs, and developed a technique for experimental research of voltage quality in power networks and elimination of their negative effects The values of voltage and current were determined for the first time to analyze the harmonic content of the main elements of the power supply system, which are necessary to eliminate the measures.

The main characteristics of uninterruptible power consumers are recommended to determine the utilization factor, maximum factor, shape factor, demand factor, and load when calculating the number of hours of maximum load when choosing electrical equipment and calculating the power required by the enterprise.

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