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STUDY OF LOSSES IN HIGH-VOLTAGE POWER NETWORKS UNDER NONLINEAR LOADS

Tarana M. Isayeva*

Department of Electronics and Automation, Azerbaijan State Oil and Industry University, Baku, Azerbaijan

Abstract. The research works devoted to the study of the problem of determining power losses in high-voltage electric networks with non-linear loads are considered, provides expressions for determining the power losses of the main network elements in a non-sinusoidal mode, and presents the results of experiments at a high-voltage substation feeding electric arc furnaces. The results of high-precision measurements of changes in active and reactive power at both ends of the power transmission line, as well as the load current of such a furnace connected to the high-voltage network through a transformer under various operating modes of the arc furnace are presented. It is shown that electric arc furnaces are very large loads with high non-linearity, which causes high power losses in the network, especially on power transmission lines and transformers. One of the effective ways to reduce such losses is to use reactive power compensators to compensate for non-linearity (reactive component of current), which is achieved by connecting capacitor banks to the lines. At the same time, this approach in combination with the calculation and correction of the systematic error of active power allows to increase the accuracy of electricity metering.

Keywords: nonlinear loads, power network, losses, active power, reactive power.

***Corresponding author:** Tarana M. Isayeva, Department of Electronics and Automation, Azerbaijan State Oil and Industry University, Baku, Azerbaijan, e-mail: *tarana.isa@gmail.com*

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1 Introduction

Energy saving is currently one of the priority areas of economic development in the modern world. The relevance of energy saving problems is largely due to the high energy intensity of industrial production. Therefore, it is necessary to significantly reduce energy losses in industrial electrical networks.

To the study and calculation of losses under nonlinear loads in high-voltage power transmission lines a number of scientific works have been devoted (Averbukh & Prasol, 2018; Sayenko et al., 2023). Analysis of these works shows that they investigated the issues of choosing methods for analyzing and calculating electrical energy losses in various sections of lines, mainly in transformers, in non-sinusoidal modes, and studied and analyzed various approaches to solving this problem (Kamoliddinov et al., 2022). In Sima et al. (2023) the approach to power loss calculation for power transformers supplying nonlinear load is considered.

It should be noted that the increase in the number of works in this area was facilitated by the development of appropriate measuring instruments and information-measuring systems for measuring and metering of electrical power.

Measurement of total losses in overhead lines by the difference in active power at the ends of the line can be carried out by determining the systematic error of the complex for measuring the total active power of the line. Actual technical losses in the electrical network can be determined by calculation using data from multifunctional electricity meters and models of individual network elements (Balametov et al., 2017).

Power losses mainly can be resistive, capacitive and inductive losses. Besides technical and corona losses exist, leakage current and dielectric losses, also. The total losses of active power of the extra high voltage overhead power line can be determined by the parameters of the mode at the end of the transmission, considering the distribution of its parameters (Agunov et al., 2004; Petrović et al., 2018).

Calculation of losses in a power transformer, provided that these losses are specified as a percentage in relation to its nominal power, is performed by a power-meter.

2 Research Objects and Methods

The calculation functions in meters for measuring electricity are performed according to the model of an electrical network. Modern electricity meters, in addition to its accounting, can perform several additional functions. When installing meters in intelligent electricity metering systems, it is necessary to consider the need to give the meters the function of "calculating losses" with the greatest practical accuracy. Some of these functions can be assigned to microprocessor electricity meters.

The energy losses in each line wire are expressed as follows (Balametov, 2006).

$$\Delta W_L = \sum_{i=1}^{N} I_i^2 \Delta t R, \tag{1}$$

where I_i - value of current in the line; Δt - measuring interval; R - line resistance.

In this case, losses are calculated based on the nominal parameters of the transformer, considering the nominal values of current and voltage. Losses can be determined based on network parameters by distributing the total load of the feeder head section proportionally to the node loads. To divide the load losses in the network into energy losses in lines and distribution transformers, the equivalent resistance is presented as two series-connected equivalent resistances of the lines and the transformer itself. To calculate losses in feeders of distribution electrical networks, the "equivalent active resistance" method can be used (Balametov et al., 2008; Balametov & Isaeva, 2019). Active losses (P_Σ) in a power transformer are defined as the sum of active losses

$$\Delta P_{T\Sigma} = \Delta P_{TL} + \Delta P_{Tid}, \tag{2}$$

where ΔP_{TL} – active load losses; ΔP_{Tid} - active idle losses.

In this case, power losses in 110 kV and less lines, as active (P_L) and reactive (Q_L) losses are determined as follows:

$$\Delta P_L = R_L I_i^2, \qquad \Delta Q_L = X_L I_i^2, \tag{3}$$

where I_i - current value of total current at the i-th moment of time; R_L - active line resistance; X_L - inductive reactance of the line.

To perform measurements at the speed of the process corresponding to the mode, it is necessary to use the vector measurement results of the mode parameters at an efficient rate (Milojević et al., 2018). In distribution power networks with utility loads, transformers with a star-to-zero winding connection scheme are used, which have a high zero sequence resistance, approximately higher than the positive sequence resistance. In these transformers, with an asymmetrical phase load, a significant zero sequence voltage arises, which causes asymmetrical voltages in the secondary windings of the transformer. The voltage unbalance factor for the zero sequence of transformers often exceeds the permissible value.

3 Areas of Application of Calculation Methods

At high-voltage power grid junctions, including electric arc steel melting furnaces, there are sharply varying loads that cause deterioration of power quality. Despite extensive research on the impact of sharply varying loads on power quality at high-voltage power grid junctions, this remains a serious and unresolved problem.

In the power supply systems of enterprises with electric arc furnaces (EAFs), both abrupt changes in loads and the generation of harmonics occur. To study the effect of abrupt changes in nonlinear load on the quality of electric power, a study was conducted at a 220/110 kV substation connected to electric arc furnaces.

Currently, there are many devices and data-computing complexes for measuring the quality of electric power. The "SIMEAS Q" measurement-computing complex was used to measure the parameters of the 110-220 kV high-voltage network, import and analyze data.

The quality recording device measures frequency, active, reactive and apparent power, power factor, voltages, flicker dose, 1st-40th harmonics of voltage and current, total harmonic distortion, active - import and export energy of the system, reactive-inductive, capacitive energy and apparent energy.

In addition, based on these values, the processor calculates the measured quantities: powers, $\cos\varphi$, flicker dose, harmonics, etc. These values are stored in the device's memory, including information about time. The average duration of the measured parameters in "SIMEAS Q" is 1-3600 seconds. The measurement duration of deviations from the given limits is determined in the interval from 10 msec to 3600 seconds.

The power transmission lines feeding the EAFs are connected to the 220 kV network through 200 MVA autotransformers, and then to the 330 and 500 kV networks. The EAFs is fed from 35 kV buses through an 18 MVA 35/0.4 kV power furnace transformer and a 0-16 Ohm adjustable series reactor. Capacitor banks (CB) with a total capacity of 22.4 MVAr are connected to the 35 kV buses: CB-1 with a series reactor with a capacity of 9.8 MVAr and CB-2 with a capacity of 12.6 MVAr.

An experiment consisting of six series was conducted in accordance with the measurement plan. The mode parameters were measured using "SIMEAS Q" directly on the 110 kV overhead line from the 220\110\10 kV substation and at the input of ATR-2 in various modes and in accordance with the requirements for the averaging intervals of the measurement results of the quality indicators of electric power, with the mode parameters - 10 msec, 1 sec and 10 sec averaging periods of the device.

The operating cycle of the EQS is divided into three characteristic periods: during the power period, the charge is heated, and the metal is melted; the technological period, which consists of oxidation and reduction periods; the auxiliary period - during this period, the production of finished metal, preparation, cleaning and loading of the furnace are performed. The formation of high harmonics occurs mainly in the power and technological periods. During the power period, the furnace consumes the energy necessary to heat the charge and maintain the melting temperature. The duration of this period is 50-60% of the total duration of the melting process, and the energy consumption is 60-80% of the energy consumed for the entire melting. During the melting period, the arc burning mode is extremely unstable; the arc power changes sharply. The number of short circuits during the melting period is 100 or more. The allowable duration of one short circuit is 2-8 seconds.

The graphs of changes in active and reactive power at the main substation are shown in Figure 1. As a result of the analysis of the data obtained during the measurements, it was found that the load of the substation changes sharply within 1-2 seconds. Active power varies within the limits of 0-22 MW, and reactive power - within +15-12 MVAr. This was observed by a sharp change in the readings of the P, Q, I and U measuring devices.

The quality of electric power according to the voltage stability at the common connection point to the power grid is considered to comply with the requirements of the standard (Andreeva

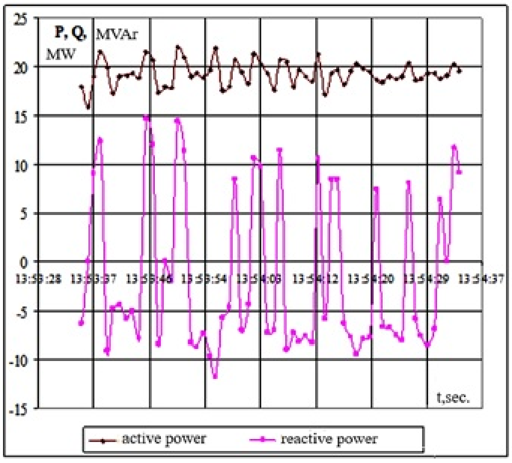

Figure 1: Results of active and reactive power registration at a 110 kV overhead line substation

et al., 2010) if all values of the voltage stability are within the interval limited by the maximum allowable values measured for each minute for a certain period of time (24 hours), and at the same time, at least 95% of the voltage stability values are within the interval limited by the normal allowable values for the same time period.

Thus, the total duration of deviations from normal permissible values does not exceed 5% of the specified period, i.e. 1 hour 12 minutes, while deviations from permissible limit values make up 0% of this period.

In addition, it is allowed to determine the compliance of the total duration of the period of exceeding the normal and maximum permissible limits of the measured values of this indicator with the norms of the standard.

Voltage oscillations are characterized by the magnitude of the voltage change and the flicker dose. For any form of periodic and non-periodic voltage oscillations, the assessment of the compliance of these oscillations with the norms of the current standard is carried out using a special measuring instrument - a flicker-meter. When the root-mean-square voltage values are registered using measuring instruments covering the measurement interval, it is possible to carry out the assessment by analytical methods.

The voltage variation range δU_i is calculated in percentage by the following formula:

$$\delta U_i = \frac{|U_i - U_{i+1}|}{U_{nom}} 100, \tag{4}$$

where U_i, U_{i+1} - are the values of the horizontal area of the envelope of successive extrema or extrema and mean square values of the fundamental frequency voltage determined in each half-period of the fundamental frequency.

The asymmetry of currents and voltages leads to an increase in electrical energy losses in networks and in electrical energy distribution elements. If the electrical circuit is loaded with inductance L current source will be described as

$$i = I_m(\sin \omega t \pm (1/3) \sin 3\omega t). \tag{5}$$

Then voltage of power supply will be

$$u = L(di/dt)(\cos \omega t \pm \cos 3\omega t). \tag{6}$$

And reactive power corresponding with these values will be determined by taking account harmonic components as follows:

$$Q = \int_{n=0}^{\infty} Q_n = U_1 I_1 sin\varphi_{11} + U_2 I_2 sin\varphi_2 + \Lambda, \tag{7}$$

where Q is reactive power; Qn is nominal value of reactive power; U_1, U_2 are voltages and I_1, I_2 - are currents of harmonic components.

Based on this expression, regardless of the sign of the 3rd harmonic, we get:

$$Q = \frac{2}{3}\,\omega \mathrm{LI}_m^2. \tag{8}$$

Reactive power, proportional to the area of the corresponding volt-ampere characteristic

$$\frac{1}{2\pi}\int_0^{2\pi} u\left(t\right)\frac{d}{dt}i\left(t\right)dt = 1. \tag{9}$$

Figure 2 shows the instantaneous power graphs corresponding to different signs of the 3rd harmonic. From these graphs, $pm(x)$ corresponds to the negative sign, and $pp(x)$ corresponds to the positive sign.

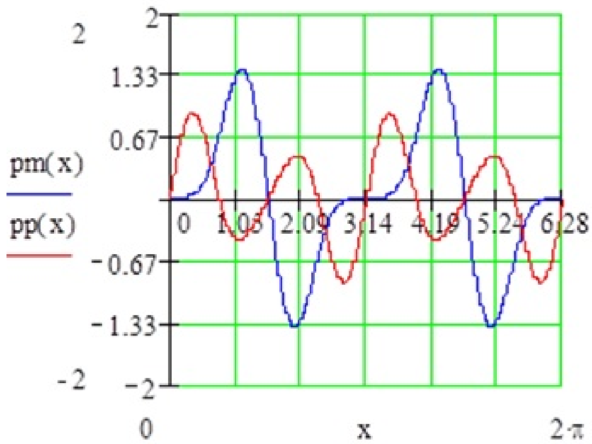

Figure 2: Instantaneous power curves with different signs in front of the 3rd harmonic

It is possible to determine the integration limits for calculating the average power using Figure 2. The repetition frequency of voltage fluctuations $F_{\delta U_t}$ (sec^{-1}, min^{-1}) is calculated by the following formula if the voltage fluctuations are periodic:

$$F_{\delta U_t} = \frac{m}{t}, \tag{10}$$

where m is the number of voltage changes in the time interval T during which measurements were made.

According to the measurement results, the number of voltage changes per minute was 22. Depending on the value of the power change, the connection of the EQS causes a voltage change within 1-3%.

The maximum permissible value for the short-term flicker dose at the common connection points of electricity consumers is 1.0, and for the long-term P_{Lt} flicker dose at the same points is 0,74. The actual value of the flicker varies between 1,4-2,3, which significantly exceeds the permissible norm.

The voltage variation limits on the 110 kV bus of the 220\110\10 kV substation when the average duration of the SIMEAS Q device is 1 second are shown in Figure 3.

At this time, the maximum and minimum voltage values at the node were recorded by the device based on measurements at a time interval of 10 msec and the average value was calculated for a time interval of 1 second. The difference between the maximum and minimum voltage values was approximately 1.5%, while the average variation of the node voltage was approximately 1.5%.

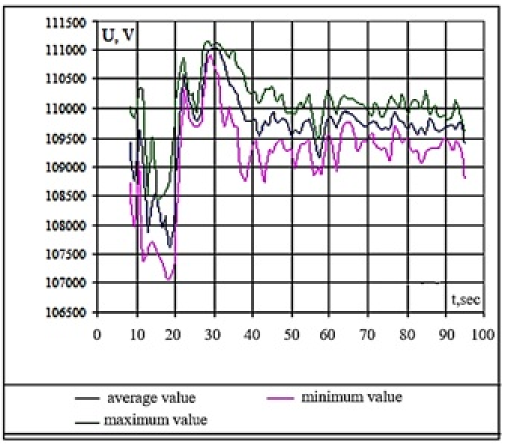

Figure 3: Graph of voltage variation on the 110 kV bus of the substation with an average duration of 1 second

When calculating the voltage variation for the case of connecting sharply changing loads, expressions analogous to those used to estimate the steady-state values of voltage losses in the network were used (Gamm et al., 2009):

$$\Delta U = \frac{\Delta Pr + \Delta Qx}{U}, \tag{11}$$

where ΔP, ΔQ - are the changes in active and reactive powers.

The limits of current variation in phase A of the 110 kV substation (Figure 4) are in the range of 50-220 A and 75-150 A when the average duration of the measuring device is 1 second.

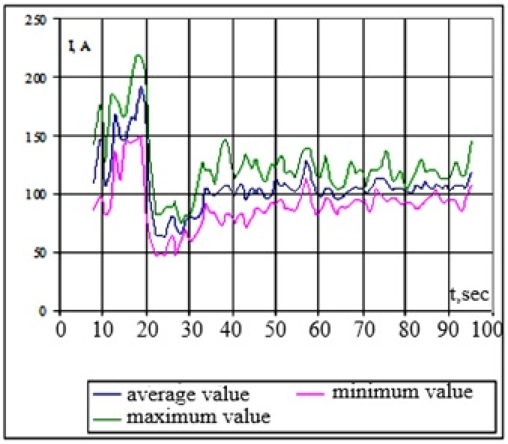

Figure 4: Graph of current change in the 110 kV phase of the substation with an average period of 1 second

The following expression is used to calculate voltage oscillations:

$$\Delta U = 100\frac{\Delta Q}{S_{shc}}, \tag{12}$$

where S_{shc} is short circuit power.

For a steelmaking company, S_{shc} = 3100 MVAr. When an ATR is operating, S_{shc} = 1550 MVAr.

4 Areas of application of calculation methods

The concept of apparent power is defined as the derivative of active power and is related to the maximum active power that can be transmitted at given values of sinusoidal current and voltage. Active power is determined as a single value, regardless of the shape of the current and voltage curves. Reactive power, on the other hand, is formally determined based on active and apparent power. However, when analyzing the operation of electrical networks and evaluating the operation of power equipment, the concept of reactive power is of great importance and indicates the level of utilization of the capabilities of network elements.

The reactive power change was $\Delta Q = 32$ MVAr. Currently, the calculated value of the voltage change on the busbars of the substation is $\Delta U = 1 - 2.5\%$, and the voltage change on the 35 kV busbars of the substation varies within the limits of 10% or more.

According to (Balametov & Khalilov, 2013), the maximum permissible voltage jump obtained from experimental data at a repetition frequency of voltage changes $F = 22$ per minute is 1.14%. Thus, the voltage sweep is much larger than the permissible one.

The asymmetry coefficient of the negative sequence voltages is less than 0.9%. The normal and permissible limit values of the asymmetry coefficient of the negative sequence voltage at the common connection points to the electrical networks are 2.0 and 4.0%, respectively. The asymmetry coefficients of the negative sequence voltage at the common connection point were within acceptable limits.

The phase currents in the 110 kV busbars of the substation vary within 50 A. The flicker dose values obtained in the measurements are shown in Table 1.

Table 1: Flicker values obtained in measurements conducted in two intervals.

Short-term flicker		
L1	**L2**	**L3**
1,95585	1,998772	2,171604
1,05553	1,024602	1,063535
L1	**L2**	**L3**
1.134734	1.245012	1.316847
2.076777	2.248981	1.929558
1.791921	2.091446	1.990125

The developed program for calculating the share of allowable consumption was tested in the test circuit. The actual consumer load connected to the 110 kV busbars of the substation is 25,000 kVA, and the transmission capacity of the junction is 400,000 kVA.

The results of calculating the impact of the consumer on the power quality indicator at the control point show that the flicker dose varies between 1.4-2.3, which is significantly higher than the norm.

This requires the use of modern automated data-measuring systems (like SCADA, PMU), microprocessor-based measuring devices (meters) (Ortiz et al., 2021). These systems and tools allow us to separately identify the components of losses and check the accuracy of energy metering systems based on measuring the current values of the regime parameters of the extra high voltage overhead line (OHL) at the ends of the power transmission line. These systems and complexes designed for measuring regime parameters allow solving many problems related to measuring information, finding and storing average values, and, together with a computer, modeling processes such as OHL regimes, corona phenomena in wires, etc., and organizing measurements at a qualitatively new level.

5 Conclusion

The results of experimental studies conducted to study the effect of a sharply changing load on the quality indicators of electric energy at a high-voltage substation show that the actual effect of a nonlinear load on certain indicators of the electricity quality, for example, on the flicker dose, is much higher than the norm. Therefore, to ensure the required quality, it is necessary to assess the allowable level of flicker dose when the nonlinear load changes sharply at the high-voltage substation at the design stage of the power plant.

Currently, in connection with the application of information and communication technologies in the power system, it has recently become appropriate to determine the total active energy losses in the overhead line by measuring the active powers at the ends of the line and using them to determine the power losses in the crown and the heating losses of the wires.

The assessment of power losses based on the difference in active powers at the ends of the EHV PTL can be performed using SCADA and PMU measurements, as well as an automated system with an intelligent meter and a special measurement system for EHV PTL. Analysis of the errors of the current power loss measurement system based on the theory of random processes allows us to obtain current values of losses in the OHL with an accuracy acceptable for practical use. In practice, it is necessary to determine the actual values of metering errors. Therefore, it is also important to determine the complexity of the errors of the electric energy metering complex, considering the actual operating conditions of the metering complex. Calculation of the systematic error of the active power metering complex and its correction allow us to increase the accuracy of electric energy metering.

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