

Analysis of the sources of higher harmonic components and their impact on the power supply system

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Abstract. This article presents the issue of sources generating higher-order harmonics is becoming increasingly urgent. In particular, problems such as additional power losses caused by these harmonics and the occurrence of ferroresonance phenomena in static compensating devices have gained primary significance. The stable and uninterrupted operation of such equipment represents one of the key factors ensuring the overall reliability of the power supply system. To eliminate these issues, it is essential already at the design stage of the power supply system to select an optimal network configuration and to improve measures aimed at maintaining the required operational quality level based on technical and regulatory criteria. However, in practical applications, the use of such devices introduces certain difficulties. In particular, their efficient operation requires the installation of dedicated filters tuned to the frequency of each individual harmonic component, which complicates the overall system configuration and makes the operation and maintenance process more challenging. At the same time, while higher-order harmonic components can be utilized purposefully when developing dedicated protection systems, their behavior under unfavorable electromagnetic conditions necessitates a deeper study of their output characteristics.

INTRODUCTION

Research findings indicate that higher-order harmonic components exert different types of influence on electromechanical relays depending on their operating principles. For instance, electromagnetic overcurrent relays are almost insensitive to higher harmonic components present in the current, whereas voltage relays exhibit a high degree of sensitivity to such distortions. Furthermore, if the proportion of higher harmonics in the voltage applied to a relay coil reaches approximately 30%, the pickup (operating) voltage becomes about 5% higher compared to the pickup voltage at the fundamental frequency. This phenomenon provides an opportunity to more accurately determine and analyze the operating voltage threshold of electromagnetic relays under distorted power-quality conditions. The occurrence of harmonic components at the nodes of an electrical network not only deteriorates the power quality indices but also leads to the emergence of Ferro resonance phenomena. This, in turn, has a significant impact on the reliability of electrical equipment, since their current-carrying capability is not unlimited. In mining enterprises, where technological processes operate continuously, the constant variation of electrical loads often results in insufficient power supply capacity. As a consequence, the reliability of electrical machines operating within the system is reduced, increasing the likelihood of malfunctions, overheating, and premature aging of insulation. In the power supply systems of mining enterprises, nonlinear loads are widely utilized. In such facilities, the load currents are typically non-sinusoidal and, in many cases, inherently nonlinear, resulting in the generation of higher-order harmonic components. Among the primary sources of harmonics in these enterprises are induction furnaces, converters, power transformers, single-phase and three-phase welding units, diode and thyristor rectifiers, and thermistors-controlled reactors. The emergence of higher harmonics caused by induction furnaces mainly occurs during the melting stage of materials. During this period, the most significant fluctuations in system voltage and the highest amplitudes of harmonic distortion-compared with other phases of the melting cycle-are observed. When welding units with rectifier-based control systems are extensively used in the power network, harmonic distortion becomes more severe, and the operating conditions of arc-related equipment become highly specific [1]. Each

particular operating mode produces its own characteristic set of harmonic components; for example, a three-phase bridge rectifier produces predominantly odd-order harmonics. The harmonic level is unstable and depends on arc ignition conditions and saturation of the welding transformer magnetic core. Minor variations in arc burning conditions can lead to either a sharp reduction or a multiple increase in current harmonics. Furthermore, any distortion of electromagnetic field symmetry in the air gap of electrical machines also leads to the generation of higher-order harmonics, thereby deteriorating machine performance and increasing electromagnetic stress within the system.

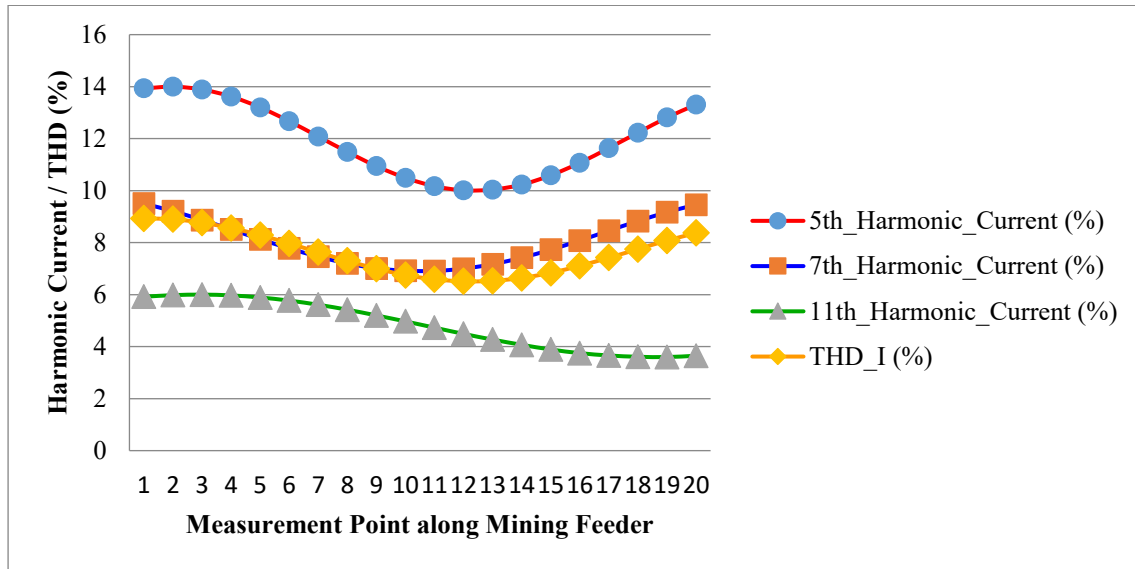


FIGURE 1. Harmonic distortion profile

At present, information on the magnitude and distribution of electric drives is fundamental for the rational solution of almost all problems related to the analysis of power systems across all voltage levels. The electrical loads of most power consumers vary over time, that is, they change within certain intervals (daily, seasonal, or annual cycles). The variability of power system loads represents an inherent characteristic of electrical networks. This phenomenon arises from the influence of numerous random factors, such as meteorological conditions, the composition and operational modes of industrial equipment, the degree of loading of technological processes, the continuity of electric transportation systems, and other external and internal operational parameters [2-5].

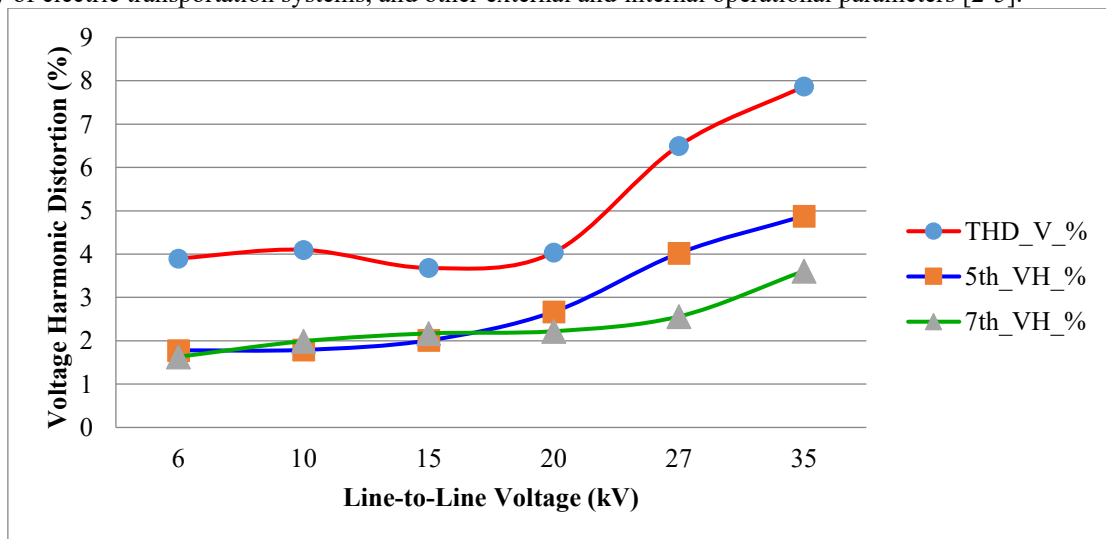


FIGURE 2. Effect of supply voltage level on voltage harmonics

The operating cycle of an induction furnace typically consists of two major stages: the metal melting process and the technological processing of the molten metal, along with short intervals between these operations. The liquid product formed during melting is periodically poured into molds, after which a new batch of charge material is loaded for the next production cycle. The duration of each melting cycle, as well as the amount of energy consumed during the process, exhibits a stepwise variable nature.

EXPERIMENTAL RESEARCH

During furnace operation, there are also short technological interruptions associated with procedures such as slag removal, addition of charge material, introduction of supplementary reagents, or performing chemical analyses. Unscheduled stops caused by emergency conditions or organizational factors occur relatively rarely; however, they still influence the unevenness of the load profile. In practice, this indicator typically ranges between 0.68 and 0.80. The furnace load exhibits small fluctuations throughout operation and may vary to some extent during transformer tap-changing events as well [6].

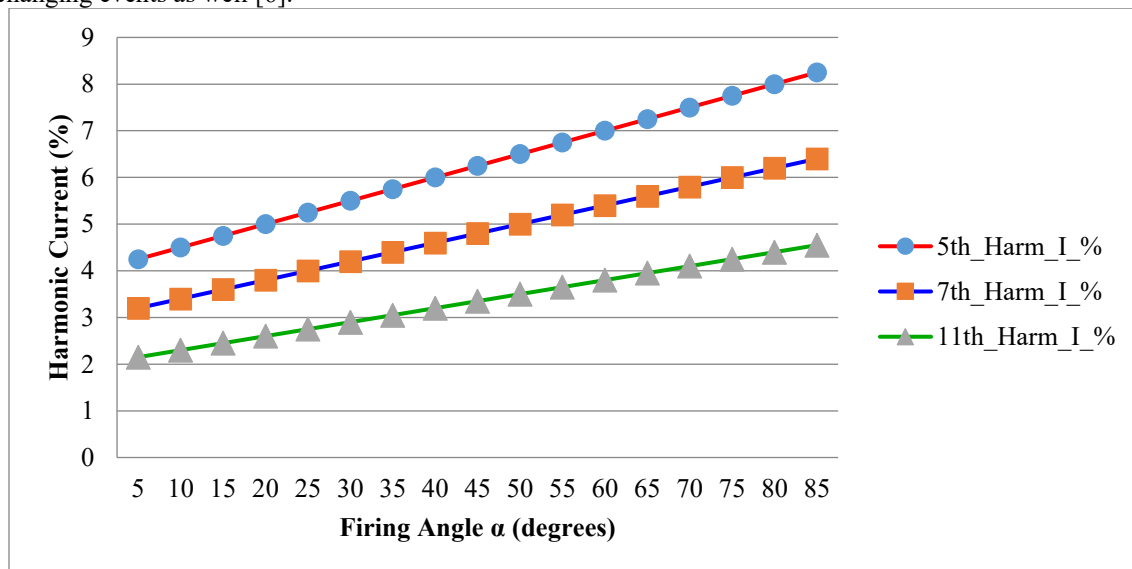


FIGURE 3. Influence of converter firing angle on harmonic currents

The effective (RMS) power in a conductor is determined by the actual time-varying load current $I(t)$, which governs the maximum thermal stress of the conductor. Based on the values of the principal parameters, it is possible to calculate the key indicators of the load curves and assess their impact on operational performance. In the analysis of factors affecting power quality, it is necessary to measure not only the electrical power quality indices but also the parameters characterizing current and power quality. For practical assessment, it is preferable to visualize the measurement results not only in numerical form but also graphically. To construct such graphs, the parameters are typically recorded over intervals ranging from one minute to forty-five minutes, with the duration of the interval depending on the characteristics of the technological process. In this context, compliance with the normative requirements for power quality indicators is evaluated, along with verification of the contractual obligations of the parties responsible for delivering high-quality electrical energy. These assessments are carried out using specialized software, which enables statistical processing and analysis of the measured data. Due to the stochastic nature of the parameters of a mining enterprise's power supply system, the load profiles are also characterized by randomness. For this reason, the evaluation of power quality indicators relies on assessing their compliance with standard requirements as well as applying a probabilistic method for monitoring and controlling power quality parameters. Losses arising from higher-order harmonics and voltage unbalance in electrical machines constitute the dominant components affecting voltage quality indicators. The losses in electrical machines mainly consist of copper losses associated with the fundamental power flow in the windings, active power losses in the steel core, and mechanical power losses [7-10].

RESEARCH RESULTS

In the presence of filter-compensation devices, the reduction of active power losses in the network occurs primarily due to the compensation of reactive power. However, in certain cases, the losses within filter-compensation equipment may exceed the losses caused by higher harmonics in a system where such compensating devices are not installed.

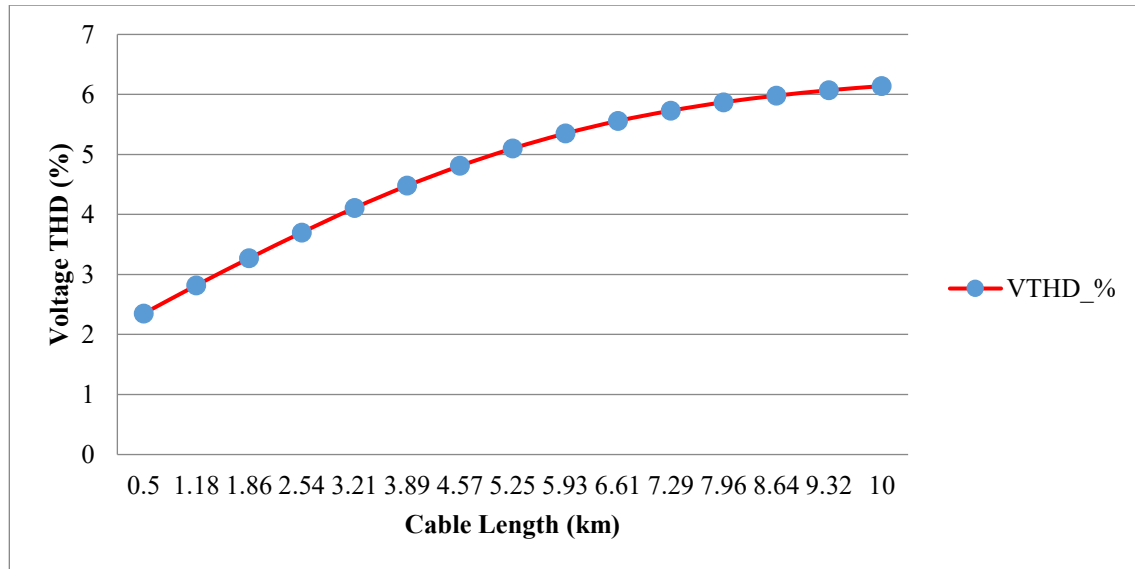


FIGURE 4. Impact of cable length on voltage THD

A methodology has been developed for collecting statistical data on the actual electrical loads and power consumption of mining enterprise consumers based on their technological group characteristics [23-52]. For a mining enterprise with a continuous technological cycle typical of precious-metal melting and casting processes, load curves have been constructed, and for the first time, it has become possible to determine their key indicators directly through graphical analysis [11-15].

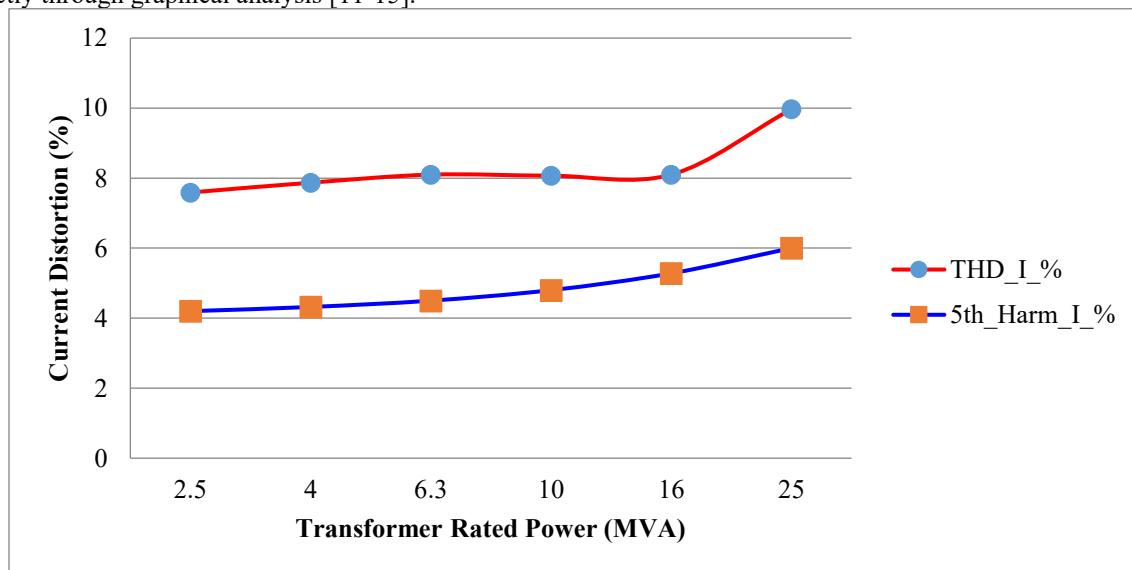


FIGURE 5. Dependence of harmonics on transformer rating

The occurrence of current harmonics throughout the network is determined by the spectral composition of no sinusoidal current and voltage waveforms, which depends on the type of electrical equipment, the nature of the harmonic sources, and their operating modes. The sources of higher-order harmonics can be identified by analyzing the voltage and current spectra of the power supply system at Ferro resonance frequencies [16-21].

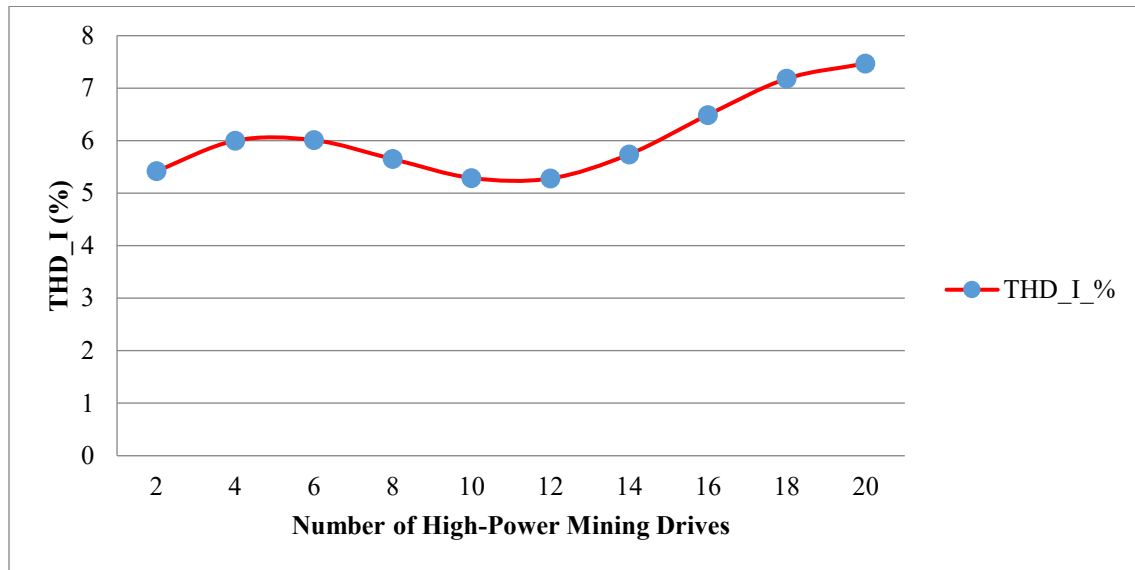


FIGURE 6. Increase of current THD with number of high-power drives

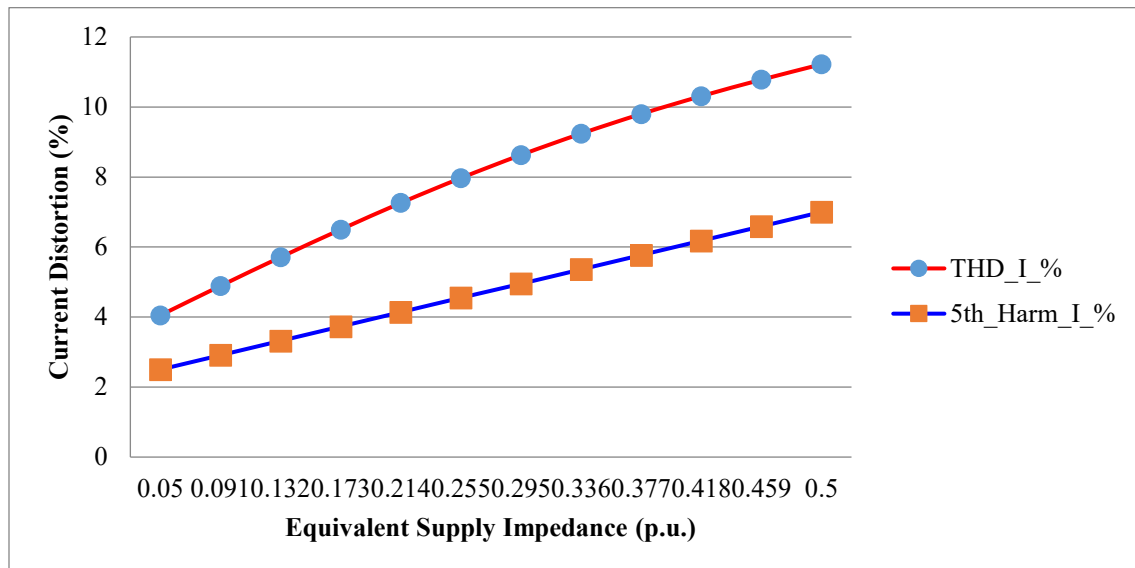


FIGURE 7. Effect of system impedance on harmonic distortion

In electrical networks containing multiple sources of higher-order harmonics, it is not possible to draw definitive conclusions regarding the causes of power quality degradation solely from the analysis of the voltage spectrum. When voltage unbalance is present in addition to waveform distortion, analytical evaluation becomes even more complex. During the operation of controlled and uncontrolled converters-which represent major sources of high current harmonics-nonstandard harmonic components may appear in the structure of unbalanced voltages.

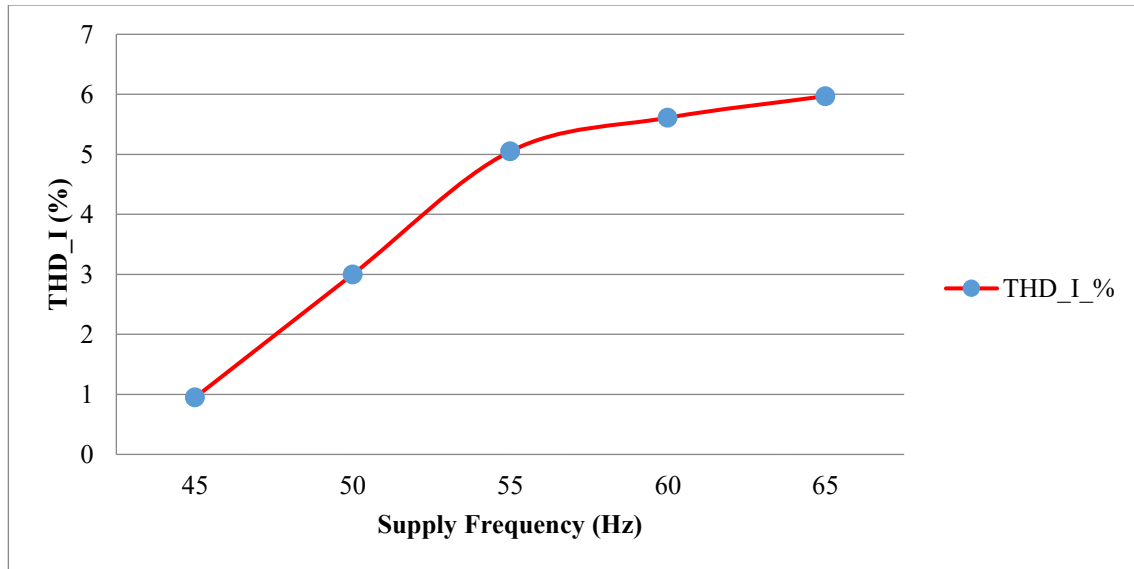


FIGURE 8. Influence of supply Frequency on current THD

In addition, supplementary losses occur in the stator and rotor steel and similar phenomena also take place in transformers and power transmission networks. In some cases, the additional losses caused by higher-order voltage harmonics increase significantly, which is characteristic of many types of electrical equipment used in mining enterprises, leading to substantial-often multimillion-kilowatt-hour-energy losses.

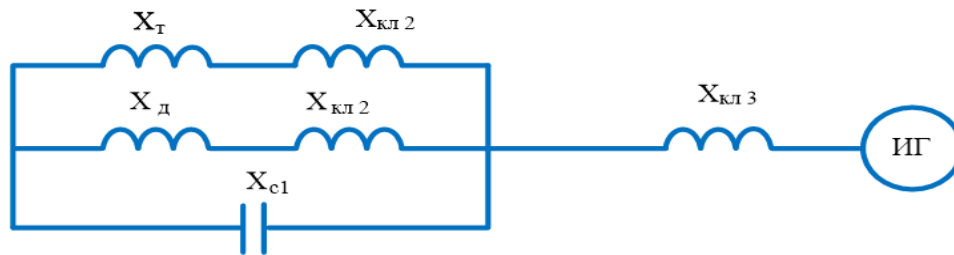


FIGURE 9. Simplified equivalent circuit of the system

Under Ferro resonance conditions, or when determining the maximum values of voltages and currents arising from Ferro resonance, it is necessary to know the voltage levels across individual elements of the system at the corresponding harmonic components. This requirement stems from the fact that each element of the system is influenced by a combination of harmonic sources. Naturally, the impedances between the high-order harmonic sources and the system elements are not identical, and therefore the voltages produced by the same harmonics will differ from one element to another. For the purpose of studying such phenomena and accelerating the analytical process, the use of specialized software tools is considered highly effective. In the classical implementation of active filters, reactors and the corresponding transformers or motors are installed at the filter output. To reduce the ripple of the compensating currents generated by the converters, inductors are connected to the output of parallel active filters in the classical configuration. Matching transformers and motors are inserted in series with the output of series active filters, where they function as booster transformers to provide the required voltage compensation. Furthermore, when matching transformers are used in high-voltage networks, they may also be installed at the outputs of parallel active filters.

CONCLUSIONS

The sources of higher-order harmonics affecting the energy equipment of mining enterprises have been identified, enabling the assessment of their power according to the type of electrical energy consumption and allowing the mitigation of processes responsible for generating harmonic components. For the first time under mining enterprise conditions, an experimental evaluation of voltage quality indicators has been conducted, making it possible to detect voltage sags, waveform distortions, and deviations in current and voltage curves within industrial power networks. The harmonic components of current and voltage in the power supply system of mining enterprises have been determined, thereby enabling preventive measures against power quality degradation and ensuring the reliability and efficiency of technological processes. Using the example of a mining enterprise, voltage quality indicators such as sinusoidal coefficients and the balance coefficients of negative- and zero-sequence components have been identified, analyzed, and evaluated for the first time. The influence characteristics of harmonic components on additional power losses in key elements of the mining enterprise power supply system-electric motors, transformers, and electrical transmission lines-have been determined. For the first time, a mathematical model has been developed to study the relationship between inductive, capacitive, and harmonic components, which made it possible to construct a Ferro resonance voltage map for the electrical networks of the enterprise. Based on the obtained harmonic characteristics of the mining enterprise's electrical system, relationships reflecting variations in capacitance and inductance during current Ferro resonance-taking into account active resistance of the network-have been established. A power-electronic complex based on a passive-filter-assisted parallel active filter has been developed. Due to the presence of a shared DC-link for both the nonlinear load and the filter, the system ensures restoration of power supply under specific operational conditions and functions as an uninterruptible power source during emergency situations in the power supply network.

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