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Gennadiy Pivnyak[1], Oleksandr Azukovskiy[2], Yurii Papaika[3], Edgar Caseres Cabana[4], Bogdan Miedziński[5], Bartosz Polnik[6], Andrzej Jamróż[7], Alla Polyanska[8]

Managing the power supply energy efficiency by means of higher harmonics

Abstract: The paper proposes an innovative solution for managing and ensuring high energy efficiency of power supply systems at high non-linear loads (the problem of non-sinusoidal voltage makes up more than 50% of electricity losses). This is realised by maintaining optimal value of reliability

✉ Corresponding Author: Alla Polyanska; e-mail: polyanska@agh.edu.pl

[1] Department of Power Engineering, Dnipro University of Technology, Ukraine; ORCID iD: 0000-0002-8462--2995; e-mail: rector@nmu.org.ua

[2] Department of Power Engineering, Dnipro University of Technology, Ukraine; ORCID iD: 0000-0003-1901--4333; e-mail: aziukovskiy_o@nmu.org.ua

[3] Department of Power Engineering, Dnipro University of Technology, Ukraine; ORCID iD: 0000-0001-6953--1705; e-mail: papaika.yu.a@nmu.org.ua

[4] Scientific Research Institute of the Center of Renewable Energy and Energy Efficiency, Universidad Nacional de San Agustin de Arequipa, Peru; ORCID iD: 0000-0002-0066-1349; e-mail: ecaceresca@unsa.edu.pe

[5] Faculty of Electrical Engineering, Wroclaw University of Science and Technology, Poland; ORCID iD: 0000--0001-5354-7024; e-mail: bogdan.miedzinski@pwr.edu.pl

[6] KOMAG Institute of Mining Technology, Poland; ORCID iD: 0000-0002-6803-3090; e-mail: bpolnik@komag.eu

[7] Faculty of Management, AGH University of Science and Technology, Poland; ORCID iD: 0000-0002-1847-8630; e-mail: ajamroz@zarz.agh.edu.pl

[8] Faculty of Management, AGH University of Science and Technology, Poland; Management and Administration, Ivano-Frankivsk National Technical University of oil and Gas Ivano-Frankivsk, Ukraine ORCID iD: 0000-0001-5169--1866; e-mail: polyanska@agh.edu.pl

indicators and high quality of power supply. The validation is carried out using analyses and tests of the quality of electromagnetic compatibility (EMC) for an increased number of powered frequency converters. It has been proven that the effective use and reduction of energy consumption can be achieved thanks to the unique technological features of the employed electrical devices. This enables a normal operation of the system with decreased power and adequate control of energy processes. The problem of predicting power losses under changing conditions in a decentralised electrical network has been solved based on the theory of electromagnetic compatibility. The influence of the mains mode parameters and the indices of instantaneous distortion of current and voltage waveforms caused by the operation of converters on the resonance phenomena in power supply systems were investigated. Recommendations were developed for the selection of proper parameters of compensators for 6–10 kV and 0.4–0.66 kV circuits based on the analysis of the optimisation problem when minimising active power losses. The results of our findings may aid parties involved in designing and maintaining power networks in various applications, such as mines, etc. Decisions to improve the energy efficiency of electrical networks fully correspond to the Concept of ensuring energy security of Ukraine.

Keywords: energy efficiency, managing power supply systems, frequency converters, higher harmonics, interharmonics

Introduction

Managing the electromagnetic compatibility at any industrial facility constitutes a result of the mutual interaction of both natural electric and magnetic fields (e.g., due to atmospheric discharges) as well as those introduced by facility operation. It can be dangerous for all electrical machines and equipment working in different environmental areas (e.g., in the powerful industrial enterprises that are supplied from high voltage transmission lines) (Figiel 2020). Therefore, in power plants, substations and/or transmission lines, extremely high values of the intensity of the electric and/or magnetic fields at the mains frequency can be encountered. They can i.e. reach up to about 25 kV/mm and 103 A/m, respectively. Apart from that, the interference due to higher frequencies is unavoidable. Operation of various types of electrical equipment, like control, alarm, or data transmission devices, may also be a source of disturbance. Changing the operating mode of electrical equipment and emergency situations (e.g., short circuits) cause rapid changes in the introduced electromagnetic fields, disturbing the stable electromagnetic environment. It is depicted, inter alia, by a change in the value of various disturbance indicators and may interfere with the operation of industrial facility automatic control systems (Pivnyak et al. 2013). The most common sources of disturbances are: overvoltages in networks during switching, short circuits, operation of lightning strike limiters, or during current disturbances in networks. Interference is also introduced by electrical equipment operating in a discontinuous mode, such as: a welder, lifting equipment, power tools, household appliances, as well as other various factors like contact transition resistance, switching time verification, drift of component parameters, or thermoelectric effects on the contacts between various materials.

It is obvious that any switching process in the power system is related to changes in the electric energy stored in inductive as well as capacitive elements of electrical devices (Mustafin et al. 2021). It is manifested by the variation of current and voltage waveforms and other parameters characterising physical processes in transient. With rare exceptions (electric arc, pulsed processes, etc.), relations between voltage and currents in transients are known from the theory of electric circuits.

Managing power supply energy efficiency involves implementing various strategies and technologies to optimise the consumption and utilisation of electricity. Here are some key approaches to consider (Popescu et al. 2020):

- ✦ Choose power supplies, transformers, and other electrical equipment that meet energy efficiency standards. In this case, we have to look for devices with high-efficiency ratings. The implementation of proper testing and monitoring of IT systems must be introduced (Pivniak et al. 2012).
- ✦ Improve power factor to minimise reactive power and reduce losses in electrical systems. Power factor correction techniques include the use of capacitors, active power factor correction circuits, and harmonic filters (Mustafin et al. 2021). Power factor correction optimizes the unpredictable changes in electrical networks during operational times.
- ✦ Implement load monitoring and management systems to ensure that energy consumption is optimised. Identify peak usage periods and take steps to reduce demand during those times, such as through load shifting or demand response programs (Sinchuk et al. 2022).
- ✦ Provide regular energy audits to identify areas of high energy consumption and potential efficiency improvements. Analyze power usage patterns, identify energy wastage, and implement corrective measures (Pivnyak et al. 2016b).
- ✦ Install power monitoring systems to track and analyze energy consumption. Real-time monitoring can help identify energy inefficiencies, voltage fluctuations, and power quality issues, enabling timely corrective actions.
- ✦ Utilise software tools that provide energy management capabilities, allowing you to monitor and control power usage across various devices and systems (Thanh and Bun 2022). These tools can enable features such as automatic power management, scheduling, and remote shutdown of idle equipment.
- ✦ Promote energy-conscious behaviour among employees and users. Encourage turning off lights and equipment when not in use, utilising power-saving features on computers and other devices, and raising awareness about the importance of energy efficiency (Polyanska et al. 2022).
- ✦ Maintain and service electrical equipment regularly to ensure optimal performance and energy efficiency. Keep equipment clean, repair any faulty components promptly, and ensure that electrical connections are properly tightened to minimize resistance and losses (Pivnyak et al. 2017).

By implementing these strategies and technologies, you can effectively manage and improve the energy efficiency of your power supply, reducing costs and environmental impact while ensuring reliable electricity for your operations.

Until recently, electromagnetic processes in electrical networks of industrial enterprises and power systems have been considered as large violations of static and dynamic stability, the occurrence of short-circuit currents, etc. (Pivnyak et al. 2016b; Thanh and Bun 2022). Energy and sustainable development are closely intertwined, and transitioning to sustainable energy systems is crucial for achieving a more equitable, prosperous, and environmentally responsible future (Polyanska et al. 2022). The analysis and calculation of transients in power systems are closely related to general problems of electromagnetic compatibility (EMC). It should be emphasised that the electromagnetic field characterizes the environment in the form of various electromagnetic interferences. Therefore, some types of electrical equipment may be considered as either interference generators (sources of noise) or objects of their influence that determine their electromagnetic compatibility. The long-term influence of electromagnetic interference on the insulation of electrical equipment may cause damage and, consequently, a short circuit. When it comes to automation, communication, and relay protection circuits, it often results in the malfunction of these systems, i.e., a violation of electromagnetic compatibility. This is due to a malfunction of the protection devices, the initiation of self-excited oscillations in the power grid, static instability, and other negative phenomena. Therefore, the study of electromagnetic transients in the enterprise power supply system should not be limited only to the calculation of short-circuit currents and the stability of the operation of power plants connected to the electrical network. It should primarily include the analysis of electromagnetic interference, which is a set of electromagnetic compatibility problems. Forecasting the levels of nonlinear electromagnetic disturbances can be carried out with the help of artificial intelligence, which opens a new page for the creation of methods for improving the energy efficiency of industrial and municipal networks (Dvorský et al. 2023).

The main contribution and novelty of this paper are as follows:

- We perform a detailed analysis of the usefulness of commonly used reliability and power quality factors in order to develop a set of new effective indicators considering the specificity of operation of both industrial enterprises and power systems.
- We use measurement data on the scope and nature of the instantaneous current and voltage waveform distortions under the technological process of industrial enterprises to improve the quality of calculations of electromagnetic and technological losses. This distinguishes our results on the estimation of energy-saving modes of power systems.
- We show that the mechanism of the optimal solution to ensure the required level of electromagnetic compatibility of the power supply system components of any industrial enterprise is twofold in nature.
- Our results of electric resonance modeling in industrial power grids allowed a reliable determination of possible resonance zones during the higher frequencies, both harmonics and interharmonics. The obtained amplitude-frequency characteristics for specified operation conditions and parameters of the power system, as well as the energy demand of a large coal company, determined the range of changes in the value of the input resonance resistance.
- This determines the size of the power system value to ensure optimal reactive power compensation under decentralised electricity distribution. The results of our findings may aid re-

searchers and professionals involved in designing and managing power networks, including those operating in mines.

The manuscript is organised as follows: Section 1 provides an introduction to the discussed topic. Section 2 discussed the matter of electromagnetic interference (EMI) within enterprise power supply systems. Section 3 presents a review of related previously published papers. Section 4 relates to electromagnetic compatibility issues of renewable energy sources (RES). Section 5 talks about interharmonics and their importance in power supply networks. Section 6 presents the results and findings of our studies, including practical feedback for power network operators and related third parties. Section 7 concludes this paper.

Solving the problem of electromagnetic compatibility corresponds to the concept of the European Union regarding the energy transition of the energy sector to a low-carbon, energy-efficient system of electricity generation and distribution. This will lead to strengthening of economic indicators and will improve the ecological situation of the densely populated countries of Europe (Kliestik et al. 2023).

1. Electromagnetic interference within enterprise power supply systems

As already mentioned, the power supply system of the enterprise is the source of several electromagnetic disturbances. They include: power lines, switchgears, bus lines, cables, as well as any automation, control, and security equipment. Emergency (transient) electromagnetic processes are mainly associated with short circuits in supplying systems and with any switching in power circuits. As a result, they are the source of randomly arising oscillatory as well as aperiodic disturbances, usually of a wide spectrum of frequencies. The stationary electromagnetic processes, accompanied by disturbances of low, medium, and high frequencies (from a few Hz up to 100 GHz), arise in all electrical power installations. Their frequency spectrum is shown in Figure 1.

Thus, electrical installations are not only a source of electromagnetic disturbances but also suffer from these perturbations in emergency and normal conditions. This mainly takes place during:

- planned switching at the high-voltage side, as well as any maneuvering processes under failure (short circuit, overlapping of power lines insulation, operations with power disconnectors, etc.);
- switching any electrical equipment containing inductive circuits and high-current equipment generating strong electric and/or magnetic fields at an industrial frequency on and off at the low voltage side;
- the use of efficient high-frequency communication devices and data transmission units, as well as the presence of voltage fluctuations with the frequency of higher harmonics, power supply interruptions of the control current circuits, etc.;
- electrostatic discharges related to a direct lightning strike to the power line or a nearby object.

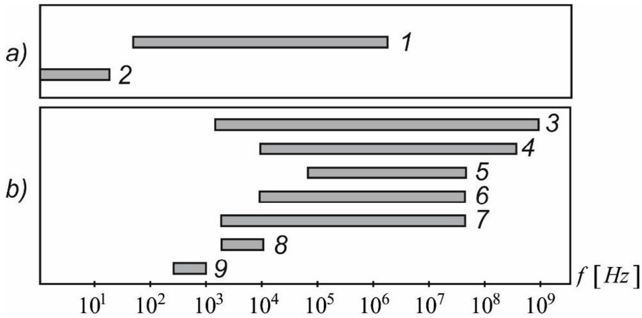


Fig. 1. Frequency spectra of arising disturbances in electrical systems and facilities due to: a) pulse electromagnetic and b) periodic processes; 1 – switching operations; 2 – load surges; 3 – radio and TV sets; 4 – computer systems; 5 – supply-line switches; 6 – electrical installations; 7 – power consumers; 8 – centralised control systems; 9 – power supply lines

Rys. 1. Widma częstotliwości powstających zaburzeń w układach i obiektach elektrycznych na skutek: a) impulsów elektromagnetycznych i b) procesów okresowych

Scheduled switching during tests and the short circuits (short circuit, overlapping of power line insulation, switching, etc.), on both high-voltage and low-voltage sides, result in harmful transient electromagnetic disturbances, primarily affecting the automation, control, and protection systems. Simultaneously, damped oscillations with frequencies of hundreds of kilohertz and overvoltages many times greater than the rated voltage may occur in high-voltage power networks. The electromagnetic disturbances during the commutation of inductive circuits are most intensive and dangerous for the technical means of low-voltage discrete automation devices. Under unfavorable conditions, under commutation of inductive loads, a significant level of disturbances, such as overvoltages, are possible to arise in power networks with a value of up to about 10 kV, at the steepness of up to 100 V/ns. The pulse rise time in the data transmission lines is funded to be in the range from 1 ns to 1 ms.

In some cases, when accepted levels are exceeded, electromagnetic disturbances may violate the immunity to disturbances of technical measures in power plants and substations. This applies to the widely used microprocessor-based safety devices. The operational reliability tests of over 100 power substations (Pivnyak et al. 2016b, 2017) have shown that even 15% of secondary devices can be damaged when they do not meet the electromagnetic compatibility requirements (Papaika et al 2017).

Selected types and characteristics of electromagnetic interference affecting the technical measures of stations and power substations are presented in Table 1.

Under a typical symmetrical power supply of industrial enterprises, background disturbances also occur. However, their level is within the limits allowed by the standards. As a rule, the content of the negative-sequence voltage component is within ±2%. The asymmetry of the three-phase voltage system for the zero sequence occurs within the same limits. The background level of non-sinusoidalities caused mainly by the asymmetry of transformer cores, as a rule, does not exceed 2–3%. In practice, non-periodic voltage dips are found associated with switching electri-

Table 1. Exemplary types and characteristics of electromagnetic interference affecting the technical means of electric power stations and substations

Tabela 1. Przykładowe rodzaje i charakterystyki zakłóceń elektromagnetycznych oddziałujących na środki techniczne stacji i podstacji elektroenergetycznych

Interference of a prolonged nature	Interference of transient nature with a high probability of appearance	Interference of transient nature with a low probability of appearance
Slow voltage variation in AC power supply systems and DC power supply systems	Supply voltage dips with a duration of no longer than 0.02 s in AC power supply systems and in DC power supply systems	Supply voltage dips with a duration of longer than 0.02 s in AC power supply systems and in DC power supply systems
Harmonics and interharmonics of supply voltage	Fluctuation of supply voltage	Outage of power in AC supply systems
Voltage of industrial frequency	Damped oscillating magnetic field	Microsecond impulse disturbances of high energy
Conductive disturbances of 0–150 kHz (excluding disturbances of 50 Hz)	Electrostatic discharges	Short appearance of voltage of industrial frequency

cal devices, such as motors, transformers, capacitors, etc. Their depth does not exceed a few percent of the rated voltage. The duration lasts from 100 ms to several seconds. On the other hand, voltage drops resulting from insulation damage due to short circuits cause a voltage reduction of up to 10%, lasting from 500 ms to a few seconds. There are also periodic voltage drops caused by the operation of controlled electronic converters. Short-term periodic and non-periodic surges, lasting up to several dozen microseconds, are also unavoidable. One of the causes are lightning strikes.

It should be noted that interharmonics (IH), most frequently occurring in electrical devices, indicate the greatest negative impact (Sinchuk et al. 2021; Dvorský et al. 2023; Kliestik et al. 2023). Such processes are also observed in the energy supply of complex thermochemical processes (Malec and Zając 2021; Thanh and Bun 2021). However, the problem of the interharmonics generation in power systems and their impact is still being studied. This is due to the complexity of the problem and its uncertainty.

2. Electromagnetic compatibility of renewable energy sources

Renewable energy sources (RES) are used more and more widely in the world (Markevychet al. 2022). In some countries, the amount of generated electricity already exceeds the value of traditional fossil-based sources. In 2015, the share of RES in the world's energy production was equal to only 5%. By 2030, it is predicted to reach 18.6%, and in 2050, to come close to 50% (Pivnyak et al.

2016; Dychkovskyi 2015a i b). This means an increase of more than 8.6 times. As for solar energy, its increase is expected to be over 30 times, with an average annual increase of 10.2%. The share of wind energy will increase 11 times during this time, with the predicted annual growth of 7.1%. The solar power plants should not normally result in significant fluctuations of the power in the system. However, this does not apply to periods of maximum feeding power under the highest intensity of solar radiation. Therefore, the impact of this unregulated and unpredictable solar energy generation must be reduced either by the influence of conventional energy sources or by taking special measures to keep the power balance in the system. The analysis of available literature shows that the assessment of a rapid change in the system load is possible to predict based on the reactive power analysis and the sinusoidal distortion coefficient (Dychkovskyi 2015b).

However, the greatest problems are related to the effective employment of wind farms, most often used in European countries (Markevych et al. 2022). This is due to the unpredictable, unstable operation of wind turbines with the wind force. As a result, the generated power is unstable and may significantly affect the stability and reliability of the power system operation (Papaika et al. 2022). The stochastic nature of the active power generated by a wind turbine results in frequency fluctuations in the system, changing both its value and the rate of change over time (Węgrzyn et al. 2022). Therefore, the quality of power energy provided to consumers decreases with visible effects such as: flickers, changes in time, as well as voltage drops (Sala and Bieda 2022). Moreover, the swinging of the turbine with the wind force leads to low-frequency oscillations of the power, which additionally ruins the stability and operation dynamics of the system (Papaika et al. 2022). It should be noted that increasing the contribution of RES in the power system reduces its inertia (time constant). Therefore, the system becomes more and more sensitive to small, short-term disturbances (Seheda et al. 2024). It is manifested, inter alia, by the appearance of low-frequency perturbations in the dynamics of its work (Kamiński et al. 2021). It is expected that this problem will gradually increase under the transformation from a centralised to a distributed system, with an increasing share of renewable energy sources (Dychkovskyi 2015a). This problem becomes especially important for large industrial enterprises. For example, it is known that the practical range of today's short-circuit power in 6–35 kV networks is within 150–1500 MVA. Meanwhile, in networks of 110–220 kV, it lies within 5000–10000 MVA. Therefore, due to the decrease in the value of a short-circuit power in particular electrical nodes for the new structure of the distributed network, it becomes necessary to theoretically re-analyze the value and flow of short-circuit currents as well as to perform appropriate coordination of the operation of the protection system (Pivnyak et al. 2016a).

3. Review of related works

Today's global strategy regarding the development and operation of the power system requires a new approach. As for the Ukrainian power system, the main limitations in its development include both technical and operational restrictions. The rapid development of renewable energy sources plays a major role here. It forces the decentralisation of the system structure and determines the electromagnetic compatibility under asymmetric operation with a non-linear load (Zhezhelenko et al. 2016).

Thus, the Ukrainian government faces the following challenges:

- introduction of market rules with the possibility to predict the energy consumption;
- creating a single model of the Unified Energy System with distributed generation compatible with the models of European Systems,
- ensuring the mode of stability and power supply reliability (Papaika et al. 2020; Khomenko et al. 2023).

Nowadays, the Ukrainian industry, above all, suffers from high power transmission losses of up to 20%. This is a lot compared to developed countries. For example, in Western Europe, they are around 4–5%, and in the United States, approx. equal to 6% (Pivnyak et al. 2013). High power losses in Ukrainian networks result mainly from ineffective reactive power compensation and the method of its regulation. Apart from this, obsolete fixed assets in electrical facilities, ineffective ways to optimize the operation of the network and voltage regulation, as well as unresolved problems of power quality had a great influence on the current situation (Beshta 2012; Papaika et al 2021). The low level of power quality significantly reduces energy efficiency in power grids, which is manifested by a change in various reliable indicators (Kolb et al. 2020). The problem of power quality is one of the important components of the complex problem of electromagnetic compatibility of a modern power supply system (PSS). Its solution is a basic step forward to improve the efficiency of power system operation. This is emphasised in the works of recognised scientists (Kosobudzki et al. 2018; Dyczko 2023). Therefore, for the effective operation of the Ukrainian power system, it is particularly important to ensure conditions for both the effective transmission and efficient consumption of electricity. It is also very important to reduce the energy consumption level of all state-owned industrial facilities (Manat and Yugay 2021).

The problem of electromagnetic compatibility and electricity quality is particularly important due to the growing use of various types of power converters in power networks. This has a direct reflection on the economic effects. According to available data, the annual losses in the world's power system, caused by the low quality of energy, reaches approx. USD500 billion per year (Zhezhelenko et al. 2016; Papaika et al. 2018). The main negative factors here are both the influence of higher harmonics as well as the asymmetry of the network operation and voltage fluctuations. According to (Vladyko et al. 2022; Sala and Bieda 2022), the annual losses resulting from this fact in Ukraine reach up to USD5.1 billion. The same results are observed in the management of other dynamic processes (Kosobudzki et al. 2017; Golovchenko et al. 2018).

4. Interharmonics and their importance

4.1. Interharmonics in power grids

Commonly, the following harmonics are distinguished in the electric power grid (Pivnyak et al. 2017; Papaika et al. 2017):

- Harmonic: $f = hf_1$, where $h > 0$ (and h is an integer).
- Interharmonic: $f \neq hf_1$, where $h > 0$ (and h is an integer).
- Sub-harmonic: $0 < f < f_1$

where: f_1 is the fundamental frequency of the power grid.

Interharmonics are not a multiple of the fundamental frequency of the system. On the amplitude-frequency spectrum, they are located between the canonical (higher) harmonics (including the fundamental on,) and the constantsand fundamental harmonic. Non-canonical harmonics, as well as subharmonics, are therefore treated as special cases of interharmonics. The IH appearing in the network, mostly due to the operation of different electrical appliances,tresults in the most harmful effect (Pivnyak et al. 2016b; Pivnyak et al. 2017; Papaika et al. 2017).

4.2. Sources of interharmonics

The interharmonics are generated under both short-term work and work in transients of any energy receiver (consumer). It is related to the rapid change of the technological proceas and the changeofin the electromagnetic field during the operation of electrical appliances (i.e., half-duplex operation of a frequency converter (FC), rectifier, etc.). In the first case, the process of changing the current (or voltage), being the source of the IH, is random and non-periodic. However, for the latter case, apart from special spontaneous cases, the IH can be considered periodically variable. Therefore, it is the basis for the approach to perform analyses and calculations of IH produced by different sources (Pivnyak et al. 2016b; Pivnyak et al. 2017). The interharmonics are due to the modulation of the fundamental and/or higher harmonics by other frequency components. It can be observed, e.g., during the operation of static frequency converters, particularly: cycloconverters, asynchronous drives, converting cascades, arc furnaces, welders, etc. The interharmoniclyhave a similar effect as the higher harmonics, but their influence is stronger. This explains the appearance of extra loss of active power and electric energy. If the nonlinear impedance Z_0, which is the source of harmonics (HH) and IH, is supplied by a sinusoidal voltage source $e_1(t)$, with impedance $Z_S(R_S, L_S)$, the instantaneous current $i(t)$ can be expressed as (Pivnyak et al. 2017):

$$i(t) = i_1(t) + i_{hh}(t) + i_{ih}(t) \tag{1}$$

where:

$i_1(t)$, $i_{hh}(t)$, $i_{ih}(t)$ – contributions due to fundamental, high and interharmonics, respectively.

Or in another form as:

$$i(t) = i_1(t) + \sum_{k=2}^{\infty} i_{hh\,k}(t) + \sum_{n=2}^{\infty} i_{ihn}(t) \tag{2}$$

As a result, the instantaneous value of the voltage $u_{AB}(t)$ at the load terminals is expressed as:

$$u_{\grave{A}\hat{A}}(t) = e_1(t) + i(t)R_s + L_s\frac{di}{dt} \tag{3}$$

Hence, the influence of the current interharmonics on the quality of the supply source can be rated.

Considering the importance of Ukraine's energy security and defense capabilities, it is vital to emphasize the importance of comprehensive studies of electromagnetic compatibility and the power supply reliability of mining enterprises. It is particularly important for the non-stationary technical and legal conditions of power systems operation and the need to transform td intelligent energy (Pivnyak et al. 2017). In view of the above, appropriatesanalyses of the specificity of the power supply systems of mining enterprises with high non-linear loads were carried out based on comprehensive tests. When assessing the energy balance of enterprises, the respective technological units have been distinguished, where the consumption of electric energy in the converted form reaches around 100% and shows the dynamics of thd "problem load" growth over the last decade (Pivnyak et al. 2017). Therefore, the commonly used electromagnetic compatibility indicatore important foofestimating the rated operation of electrical systems were analysed.

5. Results and discussion

Durihe martial law in Ukraine, more than 50% of thermal power generation facilities were damagedrtSome of the wind and solar power plantisare temporarily under Russian occupation. To maintain the country's energy securiry in a difficult time with risks of blackouts, the production of thermal coal is an important component of energy conservation and further post-war recovery and development of the industrial sector of the economy.

As a result, the main reasons and the effects of their inadequacy have been specified. The concept of ted "energy efficiency of power supply systems" has been used here as a comprehensive indicator. It considers the reliability and quality of power supply under monitoree power grid operation and the stationary conditions of mininesenterprises' installatioll. The operation conditions of the electric power systems with non-linear loads were examined, considering the decentralisation concept under designing and constructing of such networks. Therefore, appropriate studies of the working conditions antstheir changes were carried out for the main electric energy receivers used in mines.

Particular attention was paid to the relationship between the operation mode and higher harmonic content in the range of both HH and IH. As a result, the comprehensive experimental study of changes in the value of the quality indicators for voltage THD_U and curret, THDI during operatire was performedheThe main ventilation fan (MVF) and the lifting machine (ey) are shown in Figure 2. The electromagnetic disturbances caused by the operation of this type oesmachine are found to be of a cyclical nature. This allowed for assumptions of both HH and IH frequencies for further analysis of the power system operation (Pivnyak et al. 2017; Dychkovskyi 2015b).

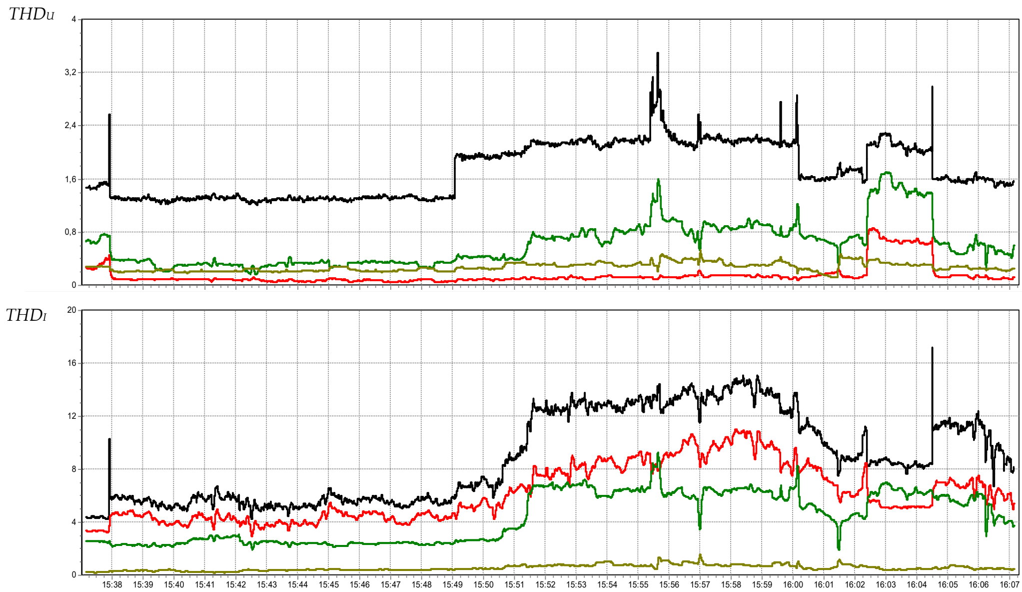


Fig. 2. Distortion of the current and voltage waveforms under start-up of the MVF:
a) voltage distortion factor THDU (black), b) current distortion factor THDI;
where red – 5th and green – 7th harmonics of voltage and current, respectively

Rys. 2. Zniekształcenie przebiegów prądu i napięcia podczas rozruchu MVF:
a) współczynnik zniekształceń napięcia THDU (czarny), b) współczynnik zniekształceń prądu THDI;
gdzie czerwony – 5. i zielony – 7. harmoniczna napięcia i prądu, odpowiednio

The asymmetry and voltage fluctuation levels during the lifting machine operation were investigated. It has been shown that under the real power system value, the unbalanced K_{2U} (negative sequence) and voltage fluctuations δU_t indicators are within the limits allowed by the regulations. Considering the specificity of underground coal mining technology to assess and forecast, the efficiency of the power system operation opens new possibilities for implementing the principles of energy efficiency and limiting final electricity consumption, as shown in Figure 3. This is because the main energy consumers that need to be considered in the energy balance are stationary electrical installations equipped with valve converters.

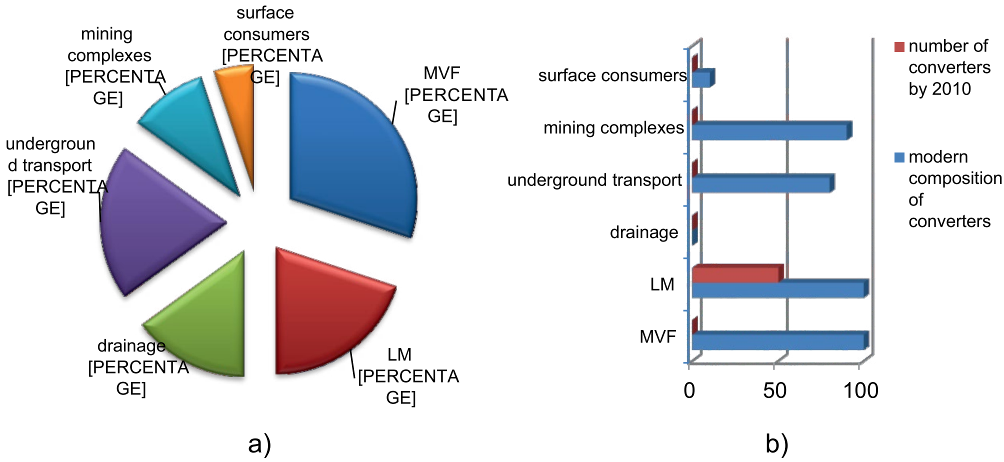


Fig. 3. Energy balance: a) due to the main technological loads of the mine;
b) and the dynamics of the increase in non-linear loads in the energy balance

Rys. 3. Bilans energetyczny: a) ze względu na główne obciążenia technologiczne kopalni;
b) oraz dynamikę wzrostu obciążeń nieliniowych w bilansie energetycznym

The analysis of the nature of harmonic disturbances during the operation of the hoisting machine (LM), powered by frequency converters, showed a significant dependence of the levels of higher harmonics of both current and voltage, measured at the station rails, on the operating cycle of the lifting machines. This proves the similarity of the velocity diagrams and the experimental graphical relationships of higher harmonics, as shown in Figures 4 and 5.

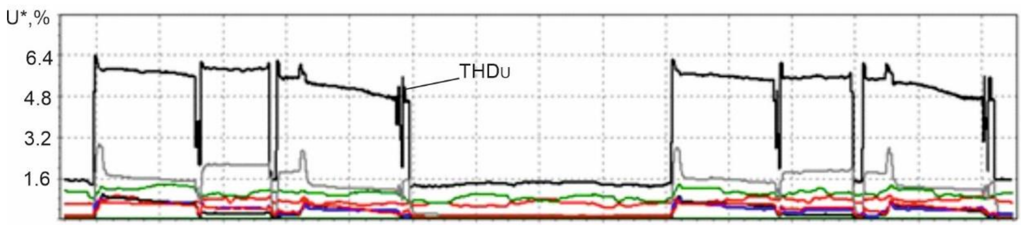


Fig. 4. Time histories of higher harmonics during coal lifting

Rys. 4. Historie czasowe wyższych harmonicznych podczas podnoszenia węgla

It should be emphasised that the measurements of higher harmonic levels were made at different distances from the mine's supply point. This allowed the assessment of the effect of elec-

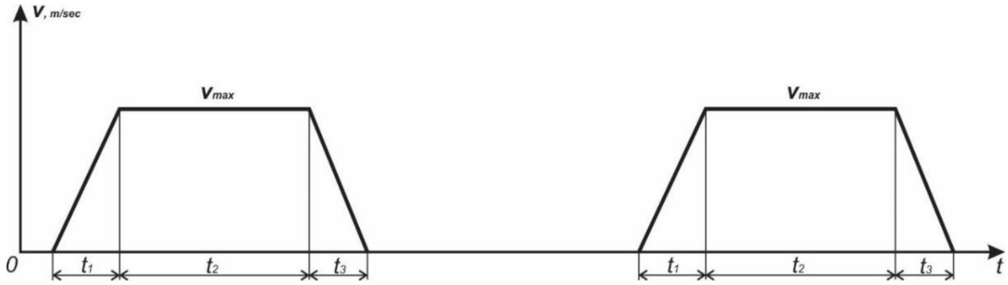


Fig. 5. Speed diagram of the hoisting machine

Rys. 5. Wykres prędkości maszyny wyciągowej

tromagnetic interference suppression on the electrical resistance of the network. The evaluation of the obtained graphs of higher harmonics enabled the formulation of important conclusions, allowing the introduction of modified distortion coefficients. They constitute the basis for a new method of determining additional electricity losses in a mine's power supply system at non-sinusoidal voltage.

The following relationships were used to develop the mean values of the coefficients:

1. Average THD_{av} value per shift/day

$$THD_{\mathrm{av}} = \frac{\sum_{i=1}^{n} THD_i \bullet t_i}{\sum_{i=1}^{n} t_i + \sum_{i=1}^{n} t_{pausei}} \tag{4}$$

where:

THD_i – the value of the distortion of voltage waveform coefficient in the *i*-th cycle of the lifting machine;

t_i – the duration of the *i*-th cycle;

2. RMS value of THD_{RMS} per shift/day

$$THD_{\mathrm{RMS}} = \sqrt{\frac{\sum_{i=1}^{n} THD_i^2 \cdot t_i}{\sum_{i=1}^{n} t_i}} \tag{5}$$

3. Utilisation coefficient:

$$K_{\mathrm{U\,THD}} = \frac{THD_{av}}{THD_{nom}} \tag{6}$$

where:

THD_{nom} – the value of the distortion coefficient of the voltage waveform, based on the rated power of the converter.

4. Maximum coefficient:

$$K_{\mathrm{M\ THD}} = \frac{THD_{max}}{THD_{av}} \tag{7}$$

where:

THD_{max} – the maximum value of the curvature of the voltage sinusoidal obtained from real graphs.

5. Switching factor:

$$K_{\mathrm{Y\ THD}} = \frac{\sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} t_i + \sum_{i=1}^{m} t_{pause\ i}} \tag{8}$$

Experimental monitoring of electrical modes and voltage quality indicators for coal mines confirms the simulation results and proves the reliability of the values of the developed coefficients of the graphs for current harmonics are described in Table 2.

Obtained values of the coefficients consider the power of the converter and the measurement data of the tachogram of the hoisting machine. This allows for the development of a more accurate method of calculating electricity losses in the power supply system of mining enterprises. This method considers the multifactorial models of changing the mining technology, as well as the parameters of the converter systems used. This is a novelty that distinguishes the current scientific achievements and can be used as an effective tool for the creation of completely new, energy-efficient transmission and distribution systems.

The problem of resonance phenomena in systems supplying significant non-linear loads has also been considered as a factor. During the modeling, the frequency bands related to the method and operation conditions of the used converters were considered. This was important for solving the characteristic equation for the complex impedance at a given load mode (9), which allowed us to obtain an analytical relationship determining the parameters of the power supply that makes optimal operation of the compensation devices possible.

The equation for determining the frequency response of the LC circuit of the supply network, which is the basis of the resonance phenomena model, has the form:

$$Z_{1\mathrm{n}} = \frac{(r_c + jx_{cn})(r_k - jx_{kn})}{r_c + r_k + j(x_{cn} - x_{kn})} = \frac{r_c + r_k(r_c + r_k) + x_{cn}^2 r_k + x_{kn}^2 r_c}{(r_c + r_k)^2 + (x_{cn} - x_{kn})^2} + j\frac{x_{cn}x_{kn}(x_{cn} - x_{kn}) + r_k^2 x_c - r_c^2 x_k}{(r_c + r_k)^2 + (x_{cn} - x_{kn})^2} \tag{9}$$

where:

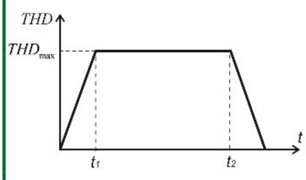
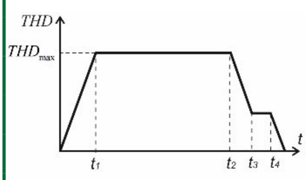
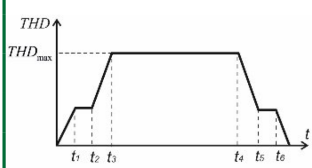
Z_{1n} – represents the resistance of complex loading on the frequency of the first harmonic,

x_{cm} – the equivalent inductive resistance of the power supply at the frequency of the *n*-th harmonic,

x_{kn} – the resistance of the capacitor bank for the *n*-th harmonic,
r_c – the total active resistance of network elements,
r_k – the rated active resistance of the capacitor bank.

Table 2. Values of coefficients of graphs of higher current harmonics

Tabela 2. Wartości współczynników wykresów wyższych harmonicznych prądu

<table>
<tr><th>Harmonic profile</th><th colspan="6">Power converter</th></tr>
<tr><td rowspan="6">
</td><td>MVA</td><td>1.0</td><td>2.0</td><td>3.0</td><td>4.0</td><td>5.0</td></tr>
<tr><td>THD_{av}</td><td>0.026</td><td>0.056</td><td>0.09</td><td>0.117</td><td>0.146</td></tr>
<tr><td>THD_{RMS}</td><td>0.003</td><td>0.011</td><td>0.025</td><td>0.044</td><td>0.069</td></tr>
<tr><td>$K_{U\ THD}$</td><td>0.44</td><td>0.51</td><td>0.52</td><td>0.51</td><td>0.52</td></tr>
<tr><td>$K_{Y\ THD}$</td><td>0.50</td><td>0.53</td><td>0.56</td><td>0.56</td><td>0.56</td></tr>
<tr><td>$K_{M\ THD}$</td><td>1.33</td><td>1.14</td><td>1.14</td><td>1.14</td><td>1.03</td></tr>
<tr><td rowspan="6">
</td><td>MVA</td><td>1.0</td><td>2.0</td><td>3.0</td><td>4.0</td><td>5.0</td></tr>
<tr><td>THD_{av}</td><td>0.025</td><td>0.054</td><td>0.08</td><td>0.111</td><td>0.131</td></tr>
<tr><td>THD_{RMS}</td><td>0.003</td><td>0.011</td><td>0.025</td><td>0.044</td><td>0.069</td></tr>
<tr><td>$K_{U\ THD}$</td><td>0.42</td><td>0.49</td><td>0.49</td><td>0.48</td><td>0.47</td></tr>
<tr><td>$K_{Y\ THD}$</td><td>0.48</td><td>0.51</td><td>0.53</td><td>0.53</td><td>0.50</td></tr>
<tr><td>$K_{M\ THD}$</td><td>1.33</td><td>1.14</td><td>1.14</td><td>1.14</td><td>1.03</td></tr>
<tr><td rowspan="6">
</td><td>MVA</td><td>1.0</td><td>2.0</td><td>3.0</td><td>4.0</td><td>5.0</td></tr>
<tr><td>THD_{av}</td><td>0.024</td><td>0.051</td><td>0.08</td><td>0.109</td><td>0.128</td></tr>
<tr><td>THD_{RMS}</td><td>0.003</td><td>0.011</td><td>0.025</td><td>0.044</td><td>0.069</td></tr>
<tr><td>$K_{U\ THD}$</td><td>0.39</td><td>0.47</td><td>0.47</td><td>0.47</td><td>0.46</td></tr>
<tr><td>$K_{Y\ THD}$</td><td>0.45</td><td>0.49</td><td>0.51</td><td>0.52</td><td>0.49</td></tr>
<tr><td>$K_{M\ THD}$</td><td>1.33</td><td>1.14</td><td>1.14</td><td>1.14</td><td>1.03</td></tr>
</table>

As shown in Figure 6, it has been found that resonance phenomena in the 6–10 kV load nodes of mining plants occur together with the evidence of both harmonic and/or interharmonic frequencies.

This is especially visible during periods of a small electrical loading, e.g., while surveying, repairing and/or when switching to a decentralised power supply.

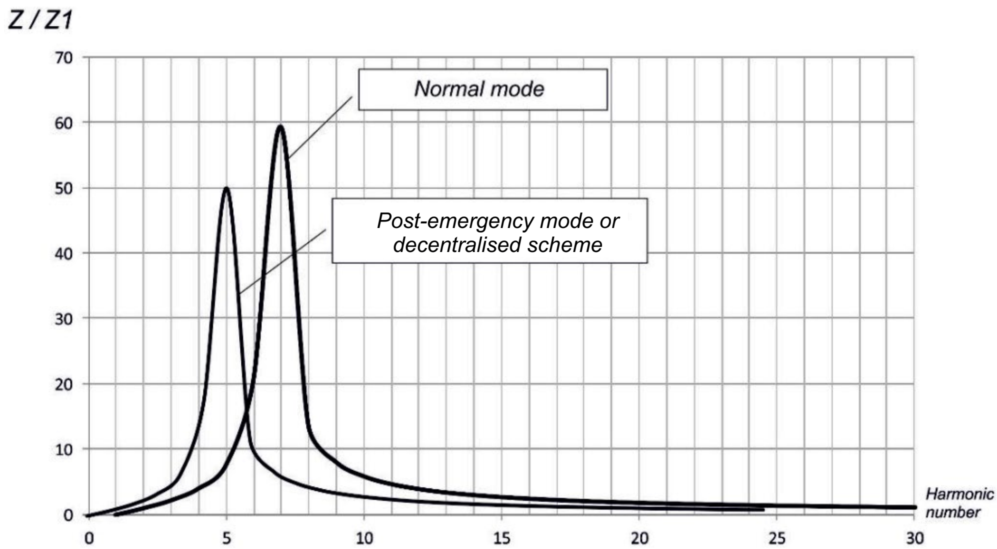


Fig. 6. Amplitude-frequency characteristics of the load unit of the mine during the transition to a decentralised power supply (Z/Z1 – relative resistance of the load node)

Rys. 6. Charakterystyki amplitudowo-częstotliwościowe odbiornika kopalni podczas przejścia na zasilanie zdecentralizowane (Z/Z1 – względna rezystancja węzła odbiorczego)

Conclusions

The analysis of the operation modes of typical electric energy loads used in industrial enterprises (especially mines) revealed their specificity, such as: cyclical work and a significant share of breaks in no-load operation. Special requirements on the construction of electrical networks and energy consumption management have been given to meet the stringent requirements regarding the reliability and safety of operation (e.g., explosion-proof). A detailed analysis of the usefulness of commonly used reliability and power quality factors encouraged the authors to develop new effective indicators considering both the specificity of work of industrial enterprises as well as power systems.

The use of measurement data on the scope and nature of the instantaneous current and voltage waveform distortions under the technological process of industrial enterprises allows for improvement in the quality of calculations of electromagnetic and technological losses. This is a novelty that distinguishes the scientific results obtained from the estimation of energy-saving modes of power systems.

It has been shown that the mechanism of the optimal solution to ensure the required level of electromagnetic compatibility of the power supply system components of any industrial enterprise is twofold in nature. First, it is important to reduce the harmonic background, which plays an important role (80%) in ensuring rational operation. Secondly, the operational reliability of the power system components deteriorated by around 20–30% during the operation of the controlled valve converters of lifting machines and fans in the mine. All this should be considered when developing effective indicators of energy quality efficiency.

The results of electric resonance modeling in industrial power grids allowed for a reliable determination of possible resonance zones during the higher frequencies, both harmonics and interharmonics. The obtained amplitude-frequency characteristics for specified operation conditions and parameters of the power system, as well as the energy demand of a large coal company, determined the range of changes in the input resonance resistance value at the level $Z/Z1$ equal to 80–120. This determines the size of the power system value to ensure optimal reactive power compensation under decentralised electricity distribution. The results of our findings may aid researchers and professionals involved in designing and managing power networks, including those operating in mines.

The theoretical foundations of the development of the theory of electromagnetic compatibility, described in this work, made it possible to determine the individual "electromagnetic traces" of industrial and municipal electrical loads. This made it possible to develop a methodology for determining the culprits in economic losses and voltage quality violations in controversial situations.

The Authors have no conflicts of interest to declare.

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Gennadiy Pivnyak, Oleksandr Azukovskiy, Yurii Papaika, Edgar Caseres Cabana,
Bogdan Miedziński, Bartosz Polnik, Andrzej Jamróż, Alla Polyanska

Zarządzanie efektywnością energetyczną zasilania za pomocą wyższych harmonicznych

Streszczenie

W artykule zaproponowano innowacyjne rozwiązanie zarządzania i zapewnienia wysokiej efektywności energetycznej systemów zasilania przy dużych obciążeniach nieliniowych (problem napięcia niesinusoidalnego stanowi ponad 50% strat energii elektrycznej). Jest to realizowane poprzez utrzymanie optymalnej wartości wskaźników niezawodności i wysokiej jakości zasilania. Walidacja jest przeprowadzana za pomocą analiz i badań jakości kompatybilności elektromagnetycznej (EMC) dla zwiększonej liczby zasilanych przemienników częstotliwości. Udowodniono, że efektywne wykorzystanie i zmniejszenie zużycia energii można osiągnąć dzięki unikalnym cechom technologicznym zastosowanych urządzeń elektrycznych. Umożliwia to normalną pracę systemu przy zmniejszonej mocy i odpowiednią kontrolę procesów energetycznych. Problem przewidywania strat mocy w zmiennych warunkach w zdecentralizowanej sieci elektrycznej został rozwiązany w oparciu o teorię kompatybilności elektromagnetycznej. Zbadano wpływ parametrów trybu sieciowego i wskaźników chwilowych zniekształceń przebiegów prądu i napięcia wywołanych pracą przemienników na zjawiska rezonansowe w systemach zasilania. Opracowano zalecenia dotyczące doboru właściwych parametrów kompensatorów dla obwodów 6–10 kV i 0,4–0,66 kV na podstawie analizy problemu optymalizacji przy minimalizacji strat mocy czynnej. Wyniki naszych ustaleń mogą pomóc stronom zaangażowanym w projektowanie i utrzymanie sieci energetycznych w różnych zastosowaniach, takich jak kopalnie itp. Decyzje dotyczące poprawy efektywności energetycznej sieci elektrycznych w pełni odpowiadają Koncepcji zapewnienia bezpieczeństwa energetycznego Ukrainy.

Słowa kluczowe: efektywność energetyczna, zarządzanie systemami zasilania, przetwornice częstotliwości, wyższe harmoniczne, interharmoniczne