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Optimization of mitigating high harmonics in 10–0.4 kV electrical distribution networks

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Abstract. Ensuring the standardized level of electric power quality and the electromagnetic compatibility of electrical equipment in industrial power supply systems is one of the key challenges of modern electrical engineering. The set of electromagnetic-environment characteristics that influence the proper operation of electrical equipment and the level of electromagnetic noise is determined by the quality of electric power within electrical supply systems. For example, such values may correspond to a network operator that is obliged to deliver high-quality electrical energy to the consumer's distribution busbars and directly to the consumer itself. In turn, the operator assumes responsibility not to degrade the power-supply quality of electrical equipment on the consumer side due to conditions within its own network. One of the key parameters defining power quality is the non-sinusoidal waveform of voltage, which arises as a result of harmonic components of current and voltage propagating through the distribution network. Voltage harmonic components up to the 40th order are associated with the following factors.

INTRODUCTION

The relevance of the problem of power-quality degradation in distribution networks is associated with the widespread integration of electrical equipment in industrial power-supply systems whose electrical loads exhibit nonlinear volt-ampere characteristics. The widespread penetration and increase of nonlinear loads within the total consumer demand are associated with their superior technical characteristics, including improved energy efficiency and advantageous mass-dimensional parameters when compared to electrical devices that possess linear volt-ampere characteristics. The development of power-electronic equipment in the energy sector has enabled the solution of numerous efficiency-related problems by providing advanced principles for controlling electric current and improving its quality. The cause of these distortions lies in the fact that the elements of converter technologies consume current in a non-sinusoidal manner. As a result, the harmonic-distorted voltage can propagate through the same distribution network and affect other industrial and residential consumers connected to it, especially those supplied by nonlinear loads. Valve-based converters-rectifiers, inverters, frequency converters, and others-represent devices constructed using power diodes (for uncontrolled converters) or thermistors and transistors (for controlled converters). Valve-type rectifiers are widely used in industry for regulating electric drives, in electrolytic and galvanic processing equipment, in various electro-technological installations, as well as in electrified railway transport systems. The phase current of a rectifier contains higher-order harmonics [1].

The amplitudes of these canonical harmonics are determined as fractions of the fundamental component and are inversely proportional to their harmonic order. The nonlinear load in industrial power-supply systems consists primarily of consumers based on valve-type rectifiers. Such consumers include, for example, variable-frequency drives, which incorporate frequency converters that make it possible to reduce electrical-energy consumption in power-supply systems by 10–25%. At the same time, the widespread use of variable-frequency drive systems in technological equipment has a significant impact on the deterioration of electric-power quality indicators. A non-sinusoidal voltage reduces the efficiency of electrical equipment and shortens its operational lifetime. Capacitor

banks are widely used in electrical networks as sources of reactive power. When capacitors operate under non-sinusoidal voltage conditions, they become overloaded by higher-order harmonic currents. Excessive loading of capacitors occurs when resonant operating conditions arise, under which the highest harmonic currents are produced.

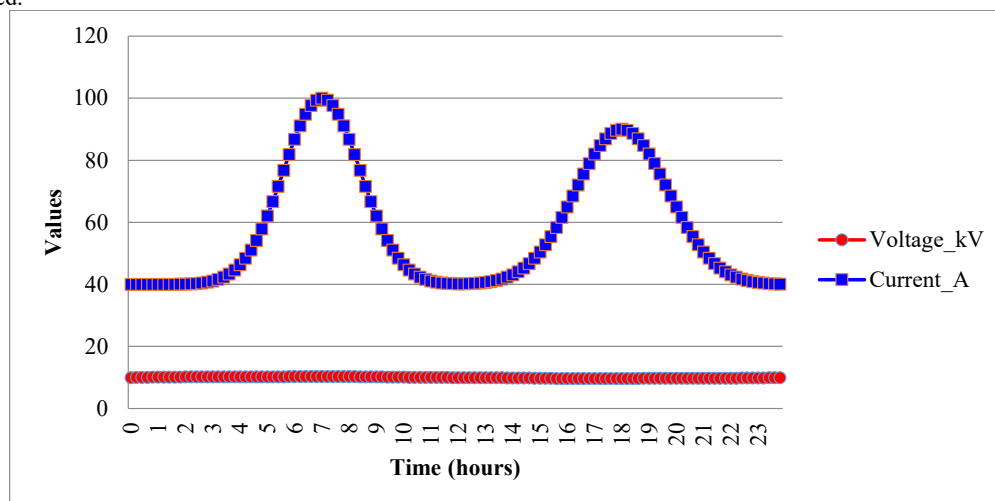


FIGURE 1. Voltage current and time

The flow of high-order harmonics through the windings of a power transformer leads to increased dielectric heating of the insulation, which in turn accelerates thermal aging and shortens the operational lifetime of the equipment [2-5].

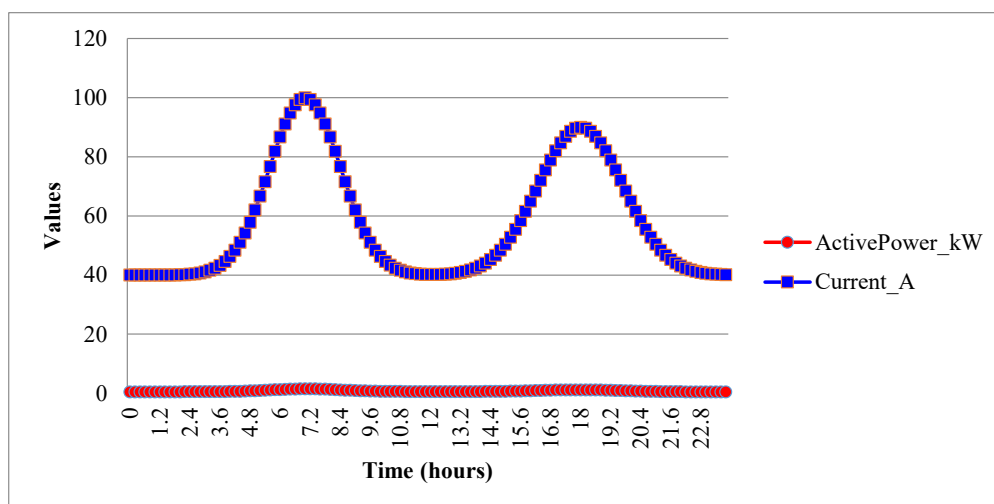


FIGURE 2. Active power and current relationship

EXPERIMENTAL RESEARCH

High-order harmonics cause an overall increase in the temperature of electrical machines, potentially reaching unacceptable levels of overheating, which can lead to damage of the excitation winding, particularly in synchronous machines [6]. Harmonics can disrupt or degrade the performance of relay protection and automation devices. Digital

relays and their algorithms are particularly sensitive to harmonic distortion, as their operating principles rely on the analysis of sampled measurement data. High-order harmonics act as electromagnetic interferences that increase the likelihood of malfunction or improper operation of electronic protection systems.

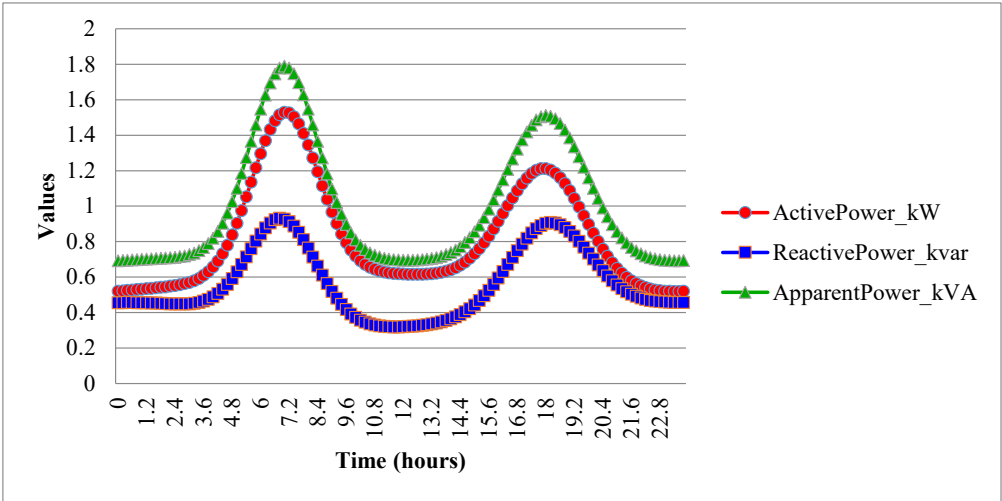


FIGURE 3. Power flow components over time

RESEARCH RESULTS

Ensuring electric power quality and maintaining the electromagnetic compatibility of electrical equipment represent critical scientific and technical challenges, the relevance of which is particularly emphasized in industrial power supply systems. This includes the need for effective reactive power compensation and the proper tuning of capacitor installations under nonlinear load conditions.

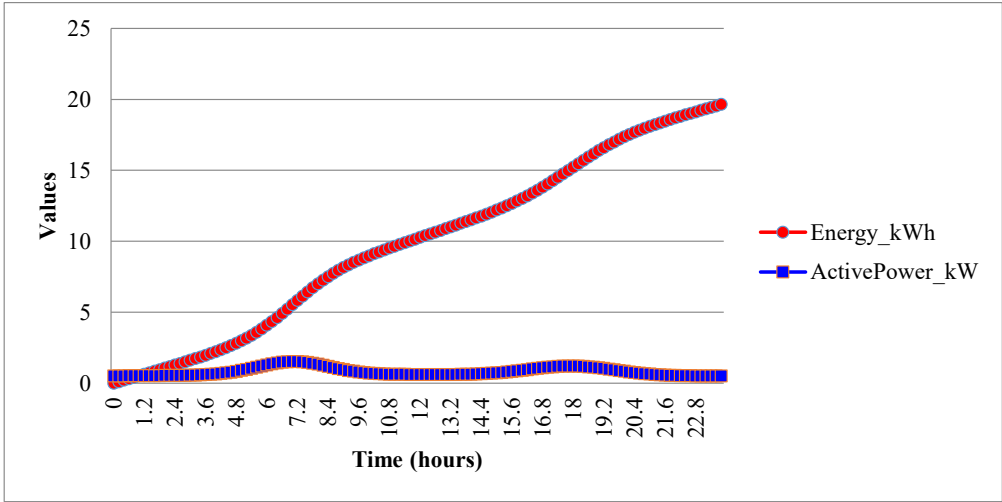


FIGURE 4. Cumulative energy and active power

The key characteristics, advantages, and limitations of national and international standards dedicated to the normalization of electric power quality indicators have been identified. The principal sources of current waveform

distortion in industrial power supply systems have been examined, including adjustable-speed electric drive systems, uninterruptible power supplies, and various electro-technological installations. A detailed analysis of the harmonic spectra generated by these devices has been conducted. Furthermore, the adverse effects of high-order harmonics on the performance of electrical equipment within power supply networks have been evaluated, revealing additional losses in capacitor banks, power transformers, and cable lines, as well as the potential for maloperation of relay protection and automation systems.

TABLE 1. The appearance of coefficient values corresponding to the odd harmonic components of the voltage waveform.

| Harmonic components of order n | The magnitude of the coefficient of the harmonic voltage component $THD_U(n), \% U_1$ | | | |
|----------------------------------|---|------|-----|---------|
| | Voltage level in electrical power networks, kV | | | |
| | 0.38 | 6-25 | 35 | 110-220 |
| 5 | 6 | 4 | 3 | 1.5 |
| 7 | 5 | 3 | 2.5 | 1 |
| 11 | 3.5 | 2 | 2 | 1 |
| 13 | 3 | 2 | 1.5 | 0.7 |
| 17 | 2 | 1.5 | 1 | 0.5 |
| 19 | 1.5 | 1 | 1 | 0.4 |
| 23 | 1.5 | 1 | 1 | 0.4 |
| 25 | 1.5 | 1 | 1 | 0.4 |
| > 25 | 1.5 | 1 | 1 | 0.4 |

The operating modes of standard power-supply schemes for various industrial electrical supply systems were modeled, taking into account different configuration options, voltage and power levels, as well as the behavior of variable linear and nonlinear loads. The tuning of these loads was performed through the application of capacitor compensation units.

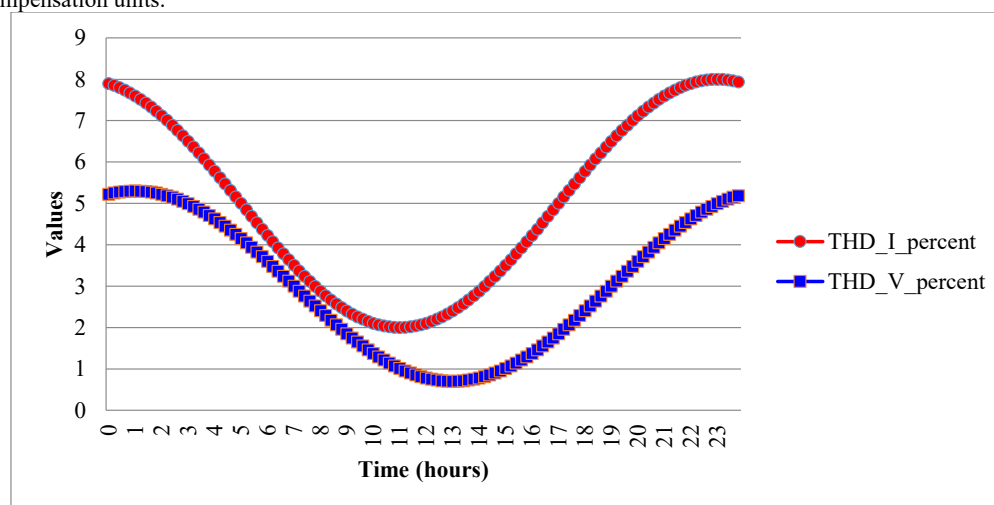


FIGURE 5. THD(I) & THD(U) distortion trends

The fundamental structural and schematic solutions for constructing a distribution network with nonlinear loads are examined. One of the key approaches is increasing the number of phases in controlled rectifier circuits. It is well known that in three-phase conversion schemes, the output current of a rectifier contains not only the fundamental harmonic but also higher-order harmonics, the orders of which are determined by the pulse number n of the rectifier configuration [7-10]. Series passive filters are designed for the full apparent power of a nonlinear load, which determines their considerable physical dimensions. Moreover, the failure of a single series filter results in the shutdown of the entire filtering branch. In contrast, shunt (parallel) passive filters operate at lower power ratings and therefore feature smaller dimensions and reduced installation costs compared to series configurations. Additionally, parallel passive filters can also be used for reactive power compensation at the fundamental frequency. Owing to

their relatively low capital and operational costs, passive filter–compensation devices are widely applied and can provide an adequate level of power quality in electrical networks [11-23].

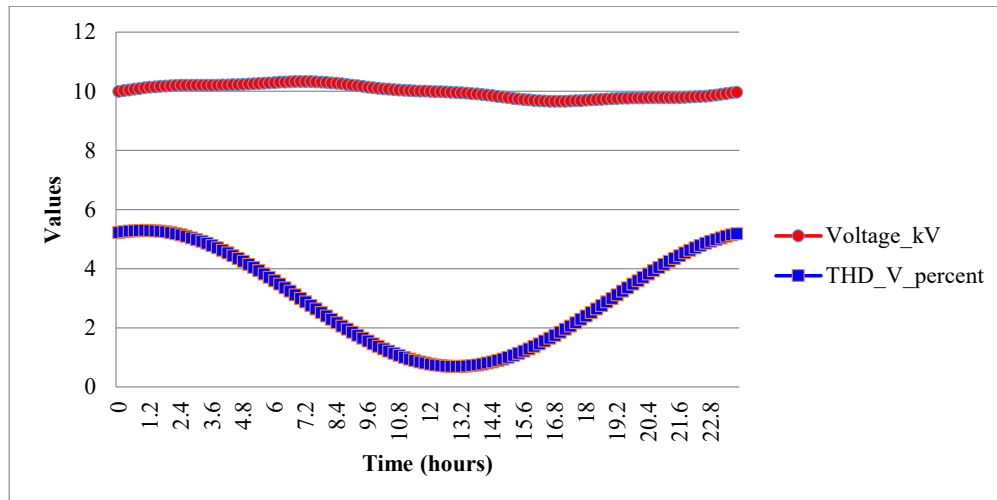


FIGURE 6. Voltage and THD(U) coupled behavior

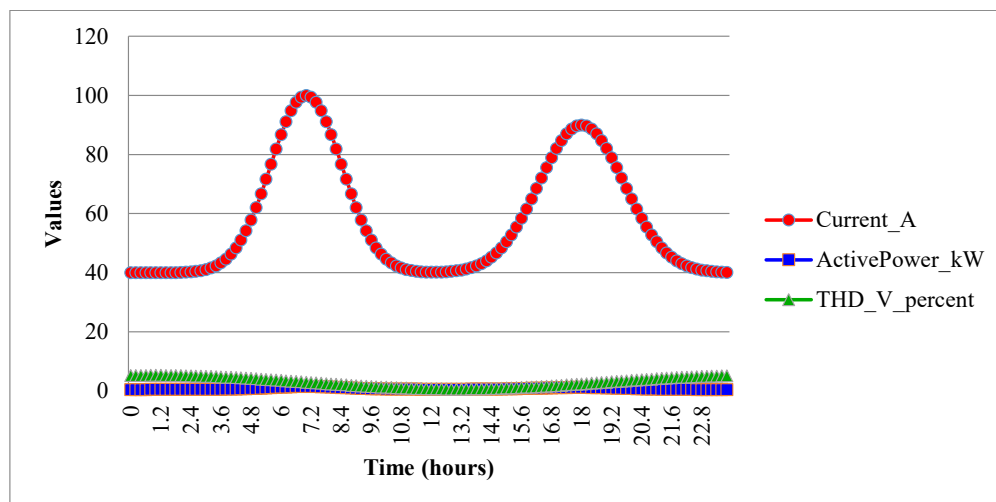


FIGURE 7. Current, power and distortion link

Passive filter–compensation devices constitute passive frequency-selective circuits that enable the attenuation of high-order harmonic amplitudes and improve the power factor of the electrical network. They do not require regular diagnostics or maintenance and have significantly lower capital costs compared with active filtering systems. However, being static devices, their effectiveness strongly depends on network parameters and on the spectral composition of currents and voltages. Furthermore, under certain conditions, a parallel resonance circuit may form between the filter parameters and the supply network at specific harmonic resonance frequencies. A shunt active filter is connected in parallel with the load that generates harmonics. Owing to its ease of integration into distribution networks and its reduced nominal power requirement (compared with series active filters), it is widely used in industrial applications [25-54]. Because the shunt active filter operates in parallel with the nonlinear load, its required rating is determined primarily by the harmonic compensation current and reactive power demand, and is therefore significantly smaller than the total current consumed by the load. A key advantage of the shunt active filter

is the presence of a programmable control unit, which governs the switching of transistor-based power converters, enabling smooth and automatic adjustment of the compensation parameters in real time. It should be emphasized that the tuning of the control algorithm and the selection of filter parameters must be carried out with respect to the configuration and operating characteristics of the compensated electrical network [24].

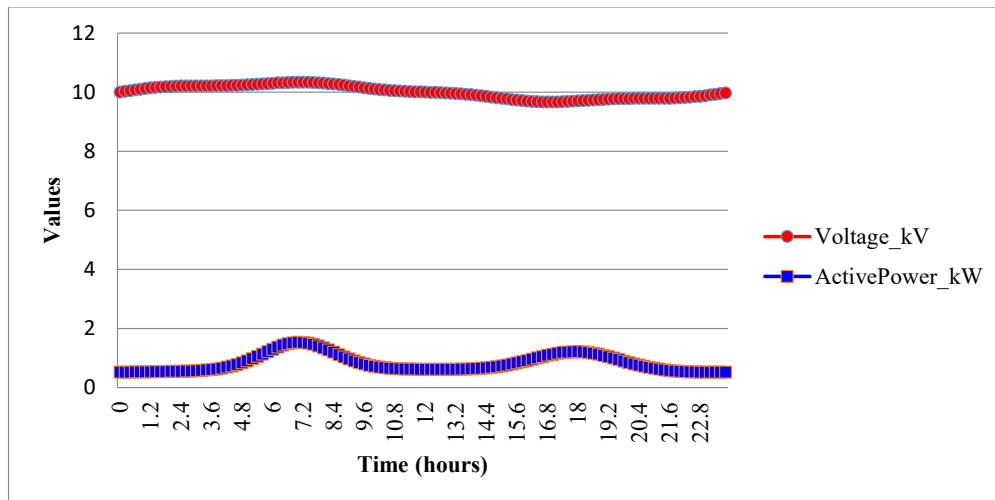
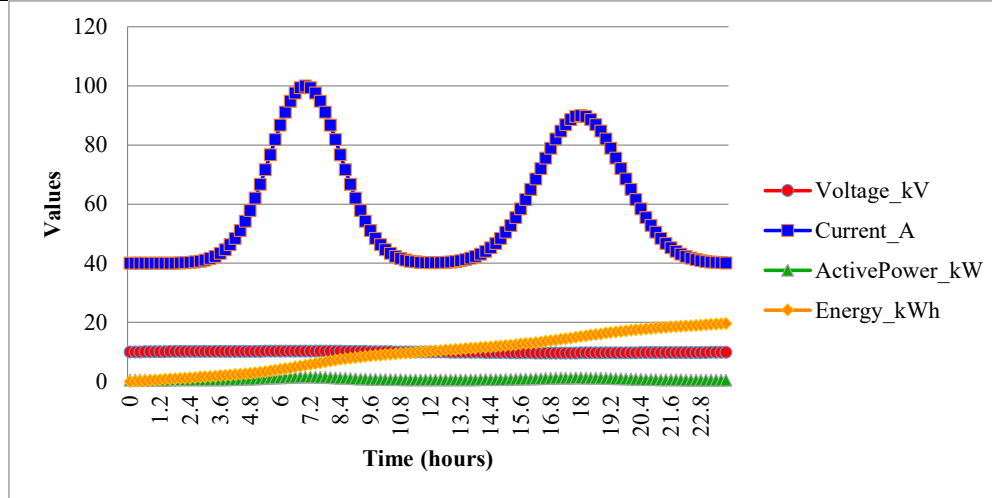


FIGURE 8. Voltage and active power correlation

One of the primary drawbacks of an active filter is its relatively high cost compared to passive filters or anti-resonance reactors. To reduce expenses and increase overall efficiency in harmonic mitigation, hybrid harmonic filters—combining both active and passive filtering stages—are employed. In such configurations, passive filters are installed to suppress those harmonic frequencies that exhibit the highest amplitude levels. Dynamic voltage sag compensators are connected to the power network through an input transformer, after which a capacitor bank is energized via a controlled thermistors rectifier. The inverter module is then supplied from the rectified voltage. The voltage inverter converts the link voltage into a compensation voltage. This compensation voltage is injected in series through the primary winding of a voltage injection transformer, thereby restoring the reduced supply voltage in the distribution network. The main technical means and solutions for compensating high-order current and voltage harmonics were analyzed, and schematic configurations for the rational construction of distribution networks with nonlinear loads were examined. In the compensation chains involving capacitor banks, as well as passive, active, and hybrid filter-compensation devices, anti-resonance reactors were applied to prevent resonant operating conditions. A detailed classification of filter-compensation devices was presented, accompanied by an analysis of their structural design features, control methods, and connection techniques within the compensated electrical network. The principal control methods for active filter-compensation devices were examined, including Park–Clarke coordinate transformations and Acai’s instantaneous power theory. Their operational characteristics, advantages, and limitations were systematically analyzed. Recommendations were developed for applying various methods and technical solutions to improve electric power quality in industrial power supply systems, considering the ratio between the nonlinear load demand and the rated capacity of the system transformer. A generalized algorithm for analyzing and modeling non sinusoidal operating modes was developed to support the rational selection of technical compensation measures. Based on this, effective power-quality improvement solutions were proposed for industrial electrical supply systems containing nonlinear loads and capacitor installations.

TABLE 2. The table shows the harmonic spectrum of the phase current for $P_d^*=0.01$ and $P_d^*=0.7$ along with the fourier series expansion of the phase current waveform at the input of the rectifier

| Harmonic order | Frequency, hz | $P_d^* = 0.7$ | | $P_d^* = 0.01$ | |
|----------------|---------------|-----------------------------------|-------|-----------------------------------|-------|
| | | Amplitude of the harmonic current | | Amplitude of the harmonic current | |
| | | A | U | A | U |
| 1 | 50 | 1397.73 | 1 | 20.38 | 1 |
| 5 | 250 | 263.92 | 0.189 | 4.10 | 0.201 |
| 7 | 350 | 177.66 | 0.127 | 2.88 | 0.141 |
| 11 | 550 | 94.52 | 0.068 | 1.84 | 0.090 |
| 13 | 650 | 70.72 | 0.051 | 1.55 | 0.076 |
| 17 | 850 | 39.53 | 0.028 | 1.18 | 0.058 |
| 19 | 950 | 29.33 | 0.021 | 1.05 | 0.052 |
| 23 | 1150 | 16.54 | 0.012 | 0.87 | 0.043 |
| 25 | 1250 | 13.18 | 0.009 | 0.79 | 0.039 |
| 29 | 1450 | 10.25 | 0.007 | 0.68 | 0.033 |
| 31 | 1550 | 9.59 | 0.007 | 0.63 | 0.031 |
| 35 | 1750 | 8.32 | 0.006 | 0.56 | 0.027 |
| 37 | 1850 | 7.54 | 0.005 | 0.52 | 0.026 |

**FIGURE 9.** Full-system performance overview

CONCLUSIONS

The operating modes of standard power-supply schemes in various industrial electrical distribution systems were modeled, taking into account different configuration options, voltage and power levels, as well as the behavior and tuning of variable linear and nonlinear loads using capacitor-compensation units. For all investigated configurations, the relative values of capacitor-bank tuning powers were determined. It was shown that resonance conditions arise at characteristic harmonic frequencies due to the operation of nonlinear loads, which may lead to unacceptable overloading of capacitor banks (with overload coefficients exceeding). Improper tuning of compensation units also results in deterioration of the voltage-quality index at the point of common coupling and causes variations in harmonic amplitudes of the nonlinear-load current. It was demonstrated that nonlinear loads in mathematical and simulation models of electrical power-supply systems should not be represented as infinite-power sources, as is often incorrectly assumed in many domestic and international studies. Instead, their representation must account for finite-capacity supply sources, whose power rating should be selected based on the characteristics of the nonlinear load and the supplying power transformer. The results of simulating the interdependencies and limitations inherent in physical, mathematical, and computer-based models show that these findings may serve as a theoretical foundation for analyzing and modeling non sinusoidal operating modes in industrial power-supply systems,

particularly under resonance phenomena. Under resonance conditions at the 7th harmonic frequency between the supply transformer and the capacitor bank, it was determined that the maximum effectiveness of compensating high-order current and voltage harmonics at the output of the active filter using a capacitive filter stage reaches 30.1% and 44.7%, respectively, when the load current decreases by 25% and the voltage drops by 5.5%. It was shown that the adverse impact of operating the active filter together with a capacitive filtering stage diminishes as the resonant harmonic order increases. For the tuned parameters of the passive section-defined by the interaction between the supply transformer and the capacitor bank-the compensation efficiency under 11th harmonic resonance conditions reaches 30.1% and 44.7% for voltage and current harmonics, respectively. In this case, the consumed current increases by 10% and the voltage sag increases by 3.4%. Using the hybrid filtering device, the dependence of high-order current and voltage harmonic levels on variations in the passive filter parameters at the active filter output was obtained. These results demonstrate that the capacitive reactance of the filter under resonant operating modes has a significant effect on the harmonic-compensation efficiency, as well as on the increase in the current drawn by the nonlinear load. The relationships governing variations in the overall power factor and the levels of high-order current and voltage harmonics in the fundamental component were determined. It was shown that the most significant influence is exerted by the capacitive-filter parameters at the output of the active section of the hybrid device, and that the degree of improvement in the total power factor depends on the nonlinear-load characteristics. An algorithm was developed for selecting the parameters of the active-capacitive filter at the output of a shunt active filter operating under resonant conditions in industrial power-supply systems with nonlinear loads and capacitor banks.

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