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## DYNAMIC MODELING OF INDUCTION MOTOR PERFORMANCE UNDER POWER QUALITY DISTURBANCES

**Abstract.** *The paper presents a dynamic electromagnetic model of a three-phase squirrel-cage asynchronous motor developed to simulate its operation under real power quality disturbances. The relevance of this work is driven by the increasing impact of electromagnetic compatibility issues and energy losses in industrial systems exposed to voltage asymmetry and harmonic distortion—conditions typical for networks with nonlinear loads such as welding equipment, arc furnaces, and frequency converters.*

*Traditional motor models, which assume ideal supply conditions, are not sufficient for accurately predicting performance degradation under such disturbances. To address this limitation, the proposed model is based on space-time complexes and an extended form of the Park–Gorev equations. A key feature of the model is the inclusion of magnetic core saturation, represented through a polynomial dependence of mutual inductance on magnetizing current, enabling more realistic simulation under high-load and unbalanced conditions.*

*The model was tested on an MTKH 112-6 motor (5.3 kW) under two scenarios: ideal sinusoidal voltage and distorted asymmetric supply with harmonics up to the 10th order. The results showed that voltage distortion leads to increased losses in the stator (from 491.3 W to 498.3 W) and rotor (from 652.2 W to 661.5 W), a decrease in efficiency (from 81.4% to 81.2%), and a significant drop in power factor (from 0.98 to 0.90). Additionally, distorted current waveforms and torque pulsations confirmed higher electromagnetic stress.*

*The model demonstrated strong agreement with experimental data (RMSE < 4%), confirming its reliability for applications in diagnostics, predictive maintenance, digital twins, and simulation environments. Unlike traditional Fourier-based approaches, the use of space-time complexes enables comprehensive modeling of both steady-state and transient processes without explicit harmonic decomposition.*

*This research contributes to the development of energy-efficient and intelligent industrial systems. Future work will focus on incorporating stochastic elements to account for dynamic variations in power quality, supporting predictive control and advanced automation within Industry 4.0.*

**Keywords:** *asynchronous motor, power quality, dynamic model, voltage asymmetry, harmonic distortion, electromagnetic simulation, efficiency.*

**Statement of the problem.** Modeling of electromechanical systems constitutes a fundamental component of modern engineering methodology, particularly at the initial stages of design, where the conceptual and functional foundations of technical systems are established. During the pre-project and preliminary development phases, critical decisions are made that determine not only the performance efficiency, but also the reliability, safety, and economic viability of the system as a whole. Traditionally, engineering design relied heavily on empirical approaches, simplified analytical methods, and iterative physical prototyping, which often resulted in increased time consumption and resource expenditures. In contrast, contemporary modeling techniques represent an advanced analytical framework that enables the prediction of system behavior prior to its physical implementation.

Within the context of electric drive system development, modeling serves as an essential tool for ensuring the coordinated and optimal interaction of system components under a wide range of operating conditions. The design process involves not only the selection of appropriate electrical machines and control strategies but also the evaluation of their dynamic performance in regimes including startup, steady-state operation, and emergency conditions. Through the application of mathematical modeling and simulation, it becomes possible to represent both electrical and mechanical subsystems within a unified computational environment, thereby facilitating the analysis of their coupled behavior.

The use of modeling techniques significantly expands the scope of analytical investigations. It allows for the identification of critical system parameters requiring optimization, the localization of energy losses, and the assessment of component durability. By systematically varying input variables—such as supply voltage, frequency, and load torque—engineers can evaluate the sensitivity of system responses and establish optimal operating conditions. This approach provides a

rigorous basis for engineering decision-making, reducing uncertainty and minimizing the need for costly design modifications at later stages.

Particular importance is attributed to the modeling of asynchronous (induction) electric motors, which remain the predominant type of electrical machines employed in industrial applications due to their structural simplicity, robustness, and cost-effectiveness. Despite these advantages, the internal physical processes of induction motors are inherently complex, involving nonlinear electromagnetic interactions, transient phenomena, magnetic saturation, and phase asymmetry. Accurate representation of these processes necessitates the use of detailed mathematical models capable of capturing both steady-state and dynamic characteristics.

The advancement of computational technologies and specialized software tools has significantly enhanced the capabilities of electromechanical modeling. Modern computer-aided design (CAD) systems and simulation platforms, including MATLAB/Simulink, ANSYS, and PSCAD, enable the development of high-fidelity models that incorporate a wide range of physical effects. These tools support the transition from simplified equivalent circuit representations to multidimensional models that account for spatial and temporal variations within the system.

Simulation environments provide the capability to analyze the dynamic behavior of electric machines under various operating scenarios. This includes the investigation of transient processes during startup and braking, response to load disturbances, and system performance under fault conditions. The visualization of mechanical characteristics, such as torque-speed dependencies, facilitates a deeper understanding of system dynamics and aids in the identification of potential instabilities, excessive thermal loading, and abnormal operating modes.

Furthermore, modeling enables comprehensive analysis of both transient and steady-state regimes, which is particularly relevant for systems employing variable frequency drives and advanced control algorithms. Through simulation, different control strategies can be evaluated in terms of their stability, efficiency, and energy consumption without the risks associated with experimental testing on physical equipment.

An additional advantage of modeling lies in its ability to establish quantitative relationships between input parameters and system responses. Variations in supply

conditions or load characteristics can be systematically examined, allowing for the development of adaptive control strategies that enhance system performance under variable operating conditions.

Modeling also plays a critical role in the development of diagnostic and predictive maintenance methodologies. By simulating various fault conditions—such as phase loss, inter-turn short circuits, and load imbalances—it is possible to identify characteristic signatures of system degradation and to design algorithms for early fault detection. This contributes to increased operational reliability and supports the transition from reactive maintenance approaches to condition-based and predictive maintenance strategies.

In summary, modeling of electromechanical systems represents an integral element of contemporary engineering science, providing a rigorous framework for the analysis, optimization, and validation of complex technical systems. It enables the integration of theoretical principles with practical design considerations, thereby enhancing the efficiency, reliability, and sustainability of engineering solutions. Under the conditions of increasing technological complexity and performance requirements, modeling serves as a key enabler of innovation and engineering advancement.

In recent decades, the development of quantitative modeling methods for electrical machines has reached a high level of sophistication, enabling researchers and engineers to simulate a wide range of operating conditions with considerable accuracy. However, as practical experience in industrial environments increasingly demonstrates, such models often remain insufficient when confronted with the complexity of real-world power supply conditions. In particular, the presence of qualitative characteristics of supply voltage—most notably voltage asymmetry and nonsinusoidal waveform distortion—introduces a level of complexity that cannot be adequately captured by conventional modeling approaches.

Voltage asymmetry, defined as the inequality of phase voltages in magnitude and/or phase displacement within a three-phase system, represents a significant deviation from the ideal symmetrical conditions assumed in classical theories. Similarly, nonsinusoidal voltage distortion, commonly referred to as harmonic distortion, arises from the superposition of higher-order harmonic components onto the fundamental sinusoidal waveform. These distortions are not merely theoretical

anomalies; rather, they are pervasive features of modern industrial power systems, where the proliferation of nonlinear electrical loads has become the norm.

A closer examination of industrial settings—particularly within large-scale manufacturing facilities—reveals the widespread use of powerful nonlinear consumers such as arc furnaces, frequency converters, variable-speed drives, and welding units. These devices, by their very nature, draw current in a discontinuous and nonlinear manner. As a consequence, they inject harmonic currents into the power network, thereby distorting the voltage waveform and contributing to phase imbalances. The electrical grid, which serves as a common coupling point for various loads, becomes a medium through which these disturbances propagate, inevitably affecting all connected equipment, including asynchronous motors.

The asynchronous motor, being one of the most widely used electromechanical energy converters in industry, is particularly sensitive to such deviations in power quality. Under conditions of voltage asymmetry, negative-sequence currents are induced within the motor windings, leading to the generation of counter-rotating magnetic fields. These fields produce additional losses and localized heating, which significantly degrade the thermal performance of the machine. Concurrently, harmonic distortion introduces pulsating torques and electromagnetic forces, resulting in mechanical vibrations, acoustic noise, and increased mechanical stress on the motor components.

As the narrative of practical operation unfolds, it becomes evident that the combined effect of asymmetry and harmonic distortion manifests in a series of detrimental phenomena. Among these are excessive heating of stator and rotor windings, increased copper and iron losses, magnetic core saturation, torque ripple, and a marked reduction in overall efficiency. Over time, these factors accelerate the aging of insulation materials, thereby shortening the operational lifespan of the motor. Furthermore, the irregular operating conditions may lead to unintended activation of protection systems, such as relay tripping, and may compromise the performance of control algorithms that are typically designed under the assumption of ideal, balanced, and sinusoidal supply conditions.

Recognizing these challenges, the scientific and engineering communities have increasingly turned their attention to the development of more advanced modeling frameworks capable of capturing the multifaceted nature of power quality

disturbances. Traditional steady-state and simplified dynamic models are gradually being supplemented—or even replaced—by approaches that incorporate the theory of symmetrical components, allowing for the decomposition of unbalanced systems into balanced sequence networks. In parallel, harmonic domain analysis provides a means of examining the interaction of individual frequency components, offering deeper insight into the effects of distortion on motor behavior.

In addition to frequency-domain techniques, time-domain modeling has emerged as a powerful tool for capturing transient and nonlinear phenomena associated with distorted supply conditions. Such models enable the explicit representation of harmonic interactions, saturation effects, and dynamic coupling between electrical and mechanical subsystems. Importantly, the reliability of these models depends not only on their mathematical rigor but also on their validation against empirical data obtained from power quality monitoring instruments deployed in real industrial environments.

The integration of simulation platforms with advanced analytical tools—such as Fast Fourier Transform (FFT) algorithms, harmonic analyzers, and power quality assessment modules—has further enhanced the ability of researchers to investigate complex electromechanical interactions. These tools facilitate the identification and quantification of harmonic components, enabling more accurate parameterization of models and more reliable prediction of system behavior under non-ideal conditions.

As the narrative progresses toward a broader perspective, it becomes clear that the future of asynchronous motor modeling lies in the adoption of holistic, multi-domain approaches. Such approaches must account not only for electrical disturbances but also for their mechanical consequences, including vibration dynamics, thermal effects, and material degradation. By bridging the gap between electrical engineering, materials science, and mechanical dynamics, researchers can develop comprehensive models that more faithfully represent the realities of industrial operation.

In conclusion, while traditional modeling techniques have provided a solid foundation for understanding the fundamental behavior of asynchronous motors, they fall short when applied to the complex and often harsh conditions of modern industrial power systems. The inclusion of voltage asymmetry and harmonic distortion into simulation frameworks is no longer optional but essential. Only

through the continued advancement of modeling methodologies—supported by empirical validation and interdisciplinary integration—can engineers ensure accurate performance evaluation, enhance energy efficiency, extend equipment lifespan, and maintain the operational reliability of asynchronous motors in real-world applications.

**Analysis of recent research and publications.** A substantial body of scientific literature, including the studies presented in papers [1–7], provides a detailed examination of the underlying causes of disturbances in power supply systems, particularly focusing on voltage asymmetry and nonsinusoidal waveform distortion. These works consistently highlight that such disturbances are primarily generated by the widespread use of nonlinear electrical loads, rapid switching processes in power electronic converters, unbalanced loading of three-phase systems, and structural imperfections within electrical networks. As modern industrial systems continue to evolve toward increased automation and electrification, the prevalence of these factors has significantly intensified, making the issue of power quality a central concern in both research and practical engineering applications.

It is well established that deviations from ideal power supply conditions have a pronounced negative impact on the operational characteristics of asynchronous machines. Numerous experimental and theoretical studies confirm that even relatively small levels of voltage asymmetry or harmonic distortion can lead to disproportionately large adverse effects. These include additional power losses, overheating of stator and rotor windings, deterioration of insulation systems, increased electromagnetic torque pulsations, mechanical vibrations, and acoustic noise. Furthermore, such conditions may result in reduced efficiency, decreased power factor, and instability in motor operation, particularly under variable load conditions. In extreme cases, prolonged exposure to poor-quality electrical energy can lead to premature failure of the machine, resulting in costly downtime and maintenance.

From a physical standpoint, the influence of voltage asymmetry manifests through the emergence of negative- and zero-sequence components in the supply system, which induce additional currents and counter-rotating magnetic fields within the motor. These phenomena not only increase thermal stress but also

disrupt the uniformity of electromagnetic torque production. On the other hand, nonsinusoidal voltage distortion introduces higher-order harmonic fields that interact with the fundamental magnetic field, giving rise to complex dynamic effects. The interaction of these harmonics can lead to resonance phenomena, localized saturation of the magnetic core, and irregular energy conversion processes within the machine.

In order to systematically evaluate and quantify the influence of these negative factors, it becomes necessary to develop an advanced mathematical model of the asynchronous motor, particularly for the widely used configuration with a short-circuited (squirrel-cage) rotor. Such a model must go beyond conventional assumptions of symmetry and sinusoidality, incorporating instead a detailed representation of power quality indices. These indices include, but are not limited to, voltage unbalance factor, total harmonic distortion (THD), individual harmonic amplitudes, frequency deviations, and phase angle distortions. Only by integrating these parameters into the model can one achieve a realistic and comprehensive analysis of motor performance under non-ideal supply conditions.

The proposed modeling approach should enable the analysis of power dependencies of the asynchronous motor as a function of varying quality parameters of the electrical grid. This implies the ability to simulate how input electrical power, electromagnetic torque, efficiency, losses, and thermal states evolve in response to changes in voltage asymmetry and harmonic content. Such a model must also account for nonlinear magnetic properties, saturation effects, and the coupling between electrical and mechanical subsystems. In addition, it is important to consider the influence of load characteristics and operating режимs, as these factors can significantly alter the sensitivity of the motor to power quality disturbances.

Modern computational tools and simulation environments provide the necessary framework for implementing such complex models. By combining time-domain simulations with frequency-domain analysis techniques—such as harmonic decomposition and spectral analysis—it becomes possible to capture both steady-state and transient behaviors of the motor. Moreover, the inclusion of real measurement data obtained from power quality analyzers can significantly enhance the accuracy and practical relevance of the model.

Recent research published in the MDPI Energies journal reflects a clear and consistent evolution in the understanding of how power quality disturbances affect the performance of induction motors. While earlier studies typically examined isolated disturbances—such as voltage unbalance, harmonic distortion, or voltage sags—modern investigations increasingly recognize that real industrial power systems are characterized by the simultaneous presence of multiple disturbances. This shift has led to the development of more comprehensive analytical frameworks, particularly those based on dynamic modeling approaches that capture the interaction between electrical, mechanical, and thermal processes within the motor.

A key contribution to this integrated perspective is presented by Paweł Gnaciński, Michał Gorniak, and Tomasz Tarasiuk (2026). Their work [8] systematically investigates the energy-efficient operation of industrial induction motors under conditions of multiple simultaneous power quality disturbances. The authors demonstrate that even when individual disturbance indices—such as total harmonic distortion (THD) or voltage unbalance factor—remain within standardized limits, their combined influence can result in a disproportionately large increase in power losses, reduced efficiency, and elevated thermal stress. This finding highlights a critical limitation of conventional power quality assessment methods, which tend to evaluate disturbances independently. The study further emphasizes that nonlinear interactions between disturbances can amplify electromagnetic torque oscillations and increase stator and rotor losses beyond expected values. Consequently, the authors advocate for the adoption of integrated modeling techniques that explicitly account for the superposition of disturbances, thereby enabling more realistic prediction of motor performance in industrial environments.

The importance of transient phenomena in the context of power quality is further elaborated in the work [9] of Marta Konuhova (2025), who develops a detailed mathematical model to simulate the response of induction motors to voltage sags. Unlike steady-state analyses, this study focuses on the dynamic behavior of the motor during both the disturbance and the recovery phase. The results show that voltage sags lead to a rapid decrease in electromagnetic torque and a corresponding increase in stator current, which may trigger protective mechanisms or cause mechanical stress. Of particular importance is the re-acceleration process following voltage recovery, during which the motor may experience prolonged instability,

oscillations in speed, and additional thermal loading. These findings underscore the necessity of incorporating time-dependent variables into the modeling framework, as steady-state approximations fail to capture the full extent of performance degradation under transient conditions.

The interaction between induction motors and the power system is further explored by Yuriy Varetsky and Marek Gajdzica (2024), who analyze power compatibility in industrial grids that include synchronous generators. Their research [10] highlights the bidirectional nature of this interaction: while poor power quality adversely affects motor operation, the behavior of induction motors—particularly during starting or large load variations—can also influence network voltage profiles. The authors demonstrate that motor starting currents can exacerbate voltage dips and distortions, thereby affecting other equipment connected to the same network. This insight reinforces the concept that induction motors should not be treated as passive loads but rather as active participants in the electrical system, whose dynamic characteristics must be considered in system-level modeling.

A substantial body of work by Paweł Gnaciński and his co-authors (2024, 2022) [11-13] provides a comprehensive investigation into complex and less conventional forms of voltage distortion, including subharmonics and interharmonics. In their 2024 study [11], the authors analyze the combined effect of voltage unbalance and subharmonics, demonstrating that this combination leads to significantly increased torque pulsations, mechanical vibrations, and acoustic noise. These effects are particularly detrimental in precision industrial applications, where even small oscillations can compromise process quality. Earlier studies (2022) [12, 13] extend this analysis to symmetrical subharmonics and interharmonics, showing that these frequency components introduce additional losses in both stator and rotor circuits. Moreover, the presence of negative-sequence subharmonics is found to be especially harmful, as it produces reverse rotating magnetic fields that increase rotor heating and reduce overall efficiency. Importantly, these studies reveal that such disturbances are increasingly common in modern power systems due to the widespread use of power electronic converters.

The influence of harmonic distortion on motor operation is further examined by Tomáš Drábek (2023), who focuses on the practical implications of high harmonic content in supply voltage. The study [14] demonstrates that harmonics contribute to

additional copper losses due to increased RMS current, as well as iron losses resulting from higher-frequency magnetic flux variations. As a result, the thermal limits of the motor are reached more quickly, necessitating derating to ensure safe operation. The author provides quantitative relationships between harmonic levels and permissible load reduction, offering valuable guidelines for industrial practitioners. This work bridges the gap between theoretical analysis and practical engineering application, highlighting the importance of incorporating power quality considerations into operational planning and equipment selection.

Complementary to this, Alfredo Gudiño-Ochoa and colleagues (2023) investigate the generation of interharmonics in induction motors supplied by variable frequency drives and AC choppers [15]. Their analysis reveals that modern power electronic systems introduce complex spectral components that interact with the motor’s electromagnetic processes, leading to additional torque ripple and potential resonance phenomena. The study emphasizes that interharmonics are not merely a byproduct of supply conditions but can also be generated within the motor-drive system itself. This finding is particularly relevant for contemporary industrial applications, where variable speed drives are widely used to improve energy efficiency but simultaneously introduce new challenges in power quality management.

From a methodological perspective, Lluís Guasch-Pesquer et al. (2022) propose an improved approach for determining the voltage unbalance factor based on induction motor behavior [16]. Traditional methods rely solely on voltage measurements, which may not accurately reflect the actual impact on the motor. By incorporating current asymmetry into the calculation, the proposed method provides a more realistic assessment of the motor’s operating conditions. This approach aligns with the broader trend toward integrating machine response into power quality evaluation, thereby enabling more accurate and application-oriented analysis.

Finally, the work of José Muñoz Táborá et al. (2020) provides a comparative analysis of the impact of harmonic distortion on induction motors of different efficiency classes (IE2, IE3, and IE4). The study reveals that higher-efficiency motors, while generally exhibiting lower baseline losses, may respond differently to harmonic distortion compared to standard-efficiency machines [17]. In some cases,

the relative increase in losses due to harmonics is more pronounced in high-efficiency motors, challenging the assumption that improved efficiency inherently implies greater robustness to power quality disturbances. This finding is particularly important in the context of modern energy policies that promote the adoption of high-efficiency equipment without fully considering the quality of the power supply.

The reviewed literature clearly indicates that the impact of power quality on induction motor performance is a multidimensional problem that cannot be adequately addressed using simplified or isolated analyses. Several important conclusions can be drawn.

First, the combined effect of multiple disturbances—such as harmonics, voltage unbalance, subharmonics, and voltage sags—results in nonlinear interactions that significantly amplify their individual impacts. Second, transient phenomena, particularly those associated with voltage sags and recovery processes, play a crucial role in determining motor stability and reliability. Third, the increasing use of power electronic converters introduces new types of disturbances, such as interharmonics, which require advanced modeling techniques. Fourth, there is a growing recognition that induction motors are active elements within the power system, contributing to and being affected by network conditions.

Taken together, these findings strongly support the need for a dynamic model-based approach to analyzing induction motor performance under non-ideal power supply conditions. Such an approach enables the integration of multiple disturbance types, the simulation of transient processes, and the evaluation of both electrical and mechanical responses of the motor. Therefore, the methodology adopted in this study is consistent with current research trends and addresses the limitations identified in existing literature.

**Objective of the study.** The aim of this study is to develop a mathematical model of an asynchronous motor that accurately reflects variations in its power-related characteristics under different levels of supply voltage quality indices, as well as to validate the effectiveness of its implementation in a software environment.

**Developing dynamic electromagnetic model operating in terms of poor-quality electric energy.**

A number of methodological approaches have been developed to account for supply voltage parameters when modeling processes in electromechanical systems

[18]. Among these, a particularly effective approach involves the use of differential equations formulated with respect to space-time complexes (STC) [3]. In this framework, the space-time complex—also referred to as a generalized vector—is defined for each variable  $Y$  and is determined as follows:

$$Y = \frac{2}{3} (Y_A + \alpha Y_B + \alpha^2 Y_C) \quad (1)$$

where  $Y_A, Y_B, Y_C$  are values of the considered variable in terms of phases. The projections of the space-time complex onto the phase axes correspond directly to the instantaneous values of the respective phase variables. In other words, the generalized vector representation enables a unified description of phase quantities by mapping them onto a coordinate system that captures both spatial and temporal variations of electromagnetic processes within the machine.

When the system of equations is formulated in terms of space-time complexes, the classical Park–Gorev equations [3], which form the theoretical foundation of widely used asynchronous motor models, can be expressed in a more generalized and analytically convenient form. This transformation allows the originally phase-based differential equations to be represented in a rotating reference frame, significantly simplifying the analysis of electromagnetic interactions.

Such an approach provides important advantages for modeling, as it enables the decoupling of variables, reduces the complexity of the system, and facilitates the inclusion of non-ideal factors such as voltage asymmetry and harmonic distortion. As a result, the Park–Gorev equations in the STC framework serve as a powerful tool for describing both steady-state and transient operating conditions of asynchronous motors, forming the basis for advanced simulation models used in modern electromechanical system analysis:

$$\underline{U}_1 = \underline{I}_1 R_1 + \underline{I}_0 R_0 + \frac{d\underline{\Psi}_1}{dt}, \quad (2)$$

$$0 = \underline{I}_2 R_2 + \underline{I}_0 R_0 + \frac{d\underline{\Psi}_2}{dt} - j\omega_m \underline{\Psi}_2, \quad (3)$$

where  $\underline{U}_1$  is STC of stator voltage,  $\underline{I}_1, \underline{I}_2, \underline{I}_0$  are STC of currents of stator, rotor, and magnetizing current,  $\underline{\Psi}_1, \underline{\Psi}_2$  are STC of stator and rotor flux linkages,  $\omega_m$  is angular velocity of AM rotation, and  $R_1, R_2$  are active stator and rotor resistances.

In the presented system of equations,  $\underline{U}_1$  denotes the space-time complex (STC) of the stator voltage. The quantities  $\underline{I}_1$ ,  $\underline{I}_2$ , and  $\underline{I}_0$  represent the STCs of the stator current, rotor current, and magnetizing current, respectively. The variables  $\underline{\Psi}_1$  and  $\underline{\Psi}_2$  correspond to the STCs of the stator and rotor flux linkages.

The parameter  $\omega_m$  defines the angular velocity of the asynchronous motor's rotation, reflecting the mechanical speed of the rotor in electromagnetic coordinates. The coefficients  $R_1$  and  $R_2$  denote the active (ohmic) resistances of the stator and rotor windings, respectively.

Such a formulation enables a compact and comprehensive representation of the electromagnetic processes occurring within the machine, allowing both electrical and mechanical variables to be analyzed within a unified mathematical framework based on space-time complexes.

A thorough analysis of asynchronous motor operation requires explicit consideration of magnetic core saturation, especially when evaluating dynamic behavior and energy-related performance indicators. This phenomenon represents a strongly nonlinear effect that substantially influences the electromechanical characteristics of the machine, including torque production, transient processes, efficiency, and thermal conditions. Neglecting saturation in modeling and design stages can result in significant discrepancies between simulated and actual performance, particularly under heavy load or non-standard operating regimes.

Magnetic saturation originates from the inherent physical properties of ferromagnetic materials used in the magnetic circuits of stator and rotor cores. At relatively low levels of magnetizing current, the magnetic domains within the material align progressively with the applied magnetic field, leading to a nearly proportional increase in magnetic flux. However, as the excitation level grows, the degree of domain alignment approaches its physical limit. Once this limit is reached, further increases in current produce only marginal growth in magnetic flux, as most domains are already oriented. This state corresponds to saturation and is characterized by a pronounced reduction in magnetic permeability.

The onset of saturation significantly modifies the electromagnetic parameters of the motor, particularly its inductive properties. Both self-inductance and mutual inductance decrease under saturated conditions, which alters the electromagnetic interactions within the machine. As a result, the motor's ability to generate torque is

affected, especially during transient events such as startup, sudden load changes, or disturbances in supply voltage. Lower inductance also increases the sensitivity of the motor to current spikes and reduces its capacity to dampen electrical perturbations. Consequently, models that ignore saturation tend to produce overly optimistic predictions, underestimating peak currents and overestimating system stability.

In addition to its impact on dynamic performance, magnetic saturation leads to higher energy losses within the motor. The nonlinear magnetization process intensifies hysteresis losses and promotes the generation of eddy currents in the core material. These losses are dissipated as heat, increasing the thermal stress on the machine. Elevated temperatures not only reduce operational efficiency but also accelerate the degradation of insulation systems, thereby decreasing the overall reliability and service life of the motor. Prolonged or repeated operation under saturated conditions may result in overheating, increased mechanical vibrations, and ultimately premature failure of critical components.

The influence of magnetic saturation is also reflected in the distortion of current waveforms. Due to the nonlinear nature of the magnetization characteristic, the resulting magnetic flux deviates from a purely sinusoidal form, which leads to the appearance of higher-order harmonics in both current and voltage. These harmonic components can spread throughout the power network, negatively impacting other connected equipment, causing electromagnetic interference, and contributing to a deterioration in overall power quality. In industrial power systems that operate multiple high-power motors simultaneously, the combined effect of such distortions can become substantial and difficult to mitigate.

To adequately represent the effects of magnetic saturation, it is necessary to employ advanced modeling techniques that go beyond linear assumptions. Such approaches include nonlinear magnetic circuit models that accurately describe the B–H characteristics of ferromagnetic materials, finite element methods (FEM) that enable detailed spatial analysis of electromagnetic fields, and the use of experimentally derived data sets or lookup tables that reflect saturation behavior in different parts of the machine. The application of these methods is particularly important in high-demand systems—such as variable-speed drive systems, electric traction applications, and automated industrial processes—where motors frequently

operate near or beyond the limits of their linear magnetic region, making precise modeling essential for reliable and efficient performance.

Magnetic saturation of the core is a key factor that must be incorporated into both the modeling and design of asynchronous motors. Its impact extends across electrical, mechanical, and thermal aspects of operation, directly influencing performance characteristics, energy efficiency, and overall reliability. A comprehensive and accurate consideration of saturation phenomena is therefore essential to ensure that motors function safely, stably, and efficiently under practical operating conditions[19]. A range of approaches exists for taking this effect into account. [3, 20-22]. Incorporating the dependence of the main mutual inductance on the magnetizing current, expressed as  $L_{12}=f(I_0)$ , provides an optimal balance between computational simplicity and modeling accuracy.

Such a relationship can be approximated using polynomial functions of even order [22], which provide a convenient way to represent the nonlinear behavior of the magnetic system. The value of the magnetizing branch inductance under unsaturated conditions is typically available in reference literature [23], or it can be estimated with sufficient accuracy based on the results of a no-load test [24].

At the same time, the identification of coefficients for the polynomial describing the dependence of inductance on the magnetizing current constitutes a separate and nontrivial problem, requiring either experimental data or parameter estimation techniques. In the present study, the formulation proposed in [25–27] was adopted as the basis for modeling.

Accordingly, when defining the expression for flux linkage, it becomes necessary to include the following components:

$$\underline{\Psi}_1 = \underline{I}_1 \cdot L_1 + L_{12}(I_0) \cdot \underline{I}_2; \underline{\Psi}_2 = \underline{I}_2 \cdot L_2 + L_{12}(I_0) \cdot \underline{I}_1 \quad (4)$$

Fig. 1 demonstrates structural diagram of the modeling object; the diagram expresses equations (2) and (3) taking into account (4).



the original system of equations with additional known relationships that describe the dynamic behavior of the system:

$$M = \frac{3}{2} p_{\tau} L_{12} \operatorname{Im}(I_1^* I_2); M - M_c = J \frac{d\omega_m}{dt} \quad (5)$$

where  $M_c$  is static moment;  $J$  is moment of inertia of a mechanical drive part; and  $p_{\tau}$  is number of pole pairs.

Software implementation of such AM model operating in terms of poor-quality power is tested by describing starting process, load rise, and steady-state mode of the motor of MTKH 112-6 type with the power of 5.3 kW. In terms of power, in case one, ideal three-phase voltage corresponding to quality indices is used; in case two, asymmetric nonsinusoidal voltage is used corresponding to real one which indices are represented in Table I. Fig. 2 demonstrates STC hodographs of the indicated voltages which show that asymmetric power stipulates elliptic hodograph shape while nonsinusoidality distorts its shape.

Table 1.

Indices of supply voltage quality

Voltage deviation in terms of phases, %								
A			B			C		
11.20			18.80			1.00		
Coefficients of harmonic constituents, %								
2	3	4	5	6	7	8	9	10
5.800	0.8300	1.69100	0.0300	2.78100	0.0300	0.08100	0.2310	0.400

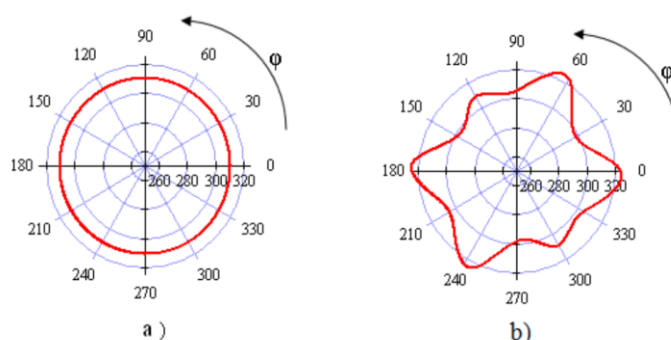


Figure 2 – Hodographs of space-time voltage complexes corresponding to indices of quality (a) and asymmetric nonsinusoidal voltage (b).

Further, there are obtained graphs of main motor coordinates. As it is seen, available harmonic constituents in AM power results in the development of moment pulsations. Fig. 3 shows instantaneous currents of stator and rotor; Fig. 4 demonstrates hodograph of asynchronous motor moment within one rotation.

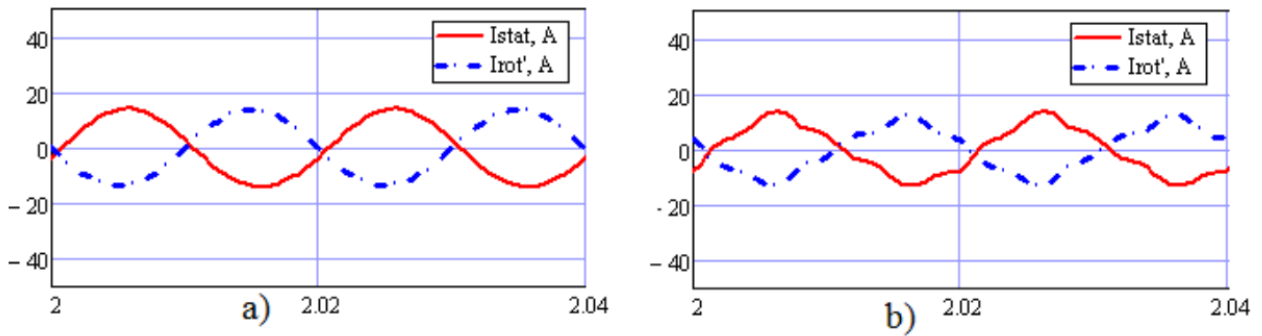


Figure 3 – Currents of stator and rotor in terms of ideal (a) and poor-quality (b) power supply in steady-state mode.

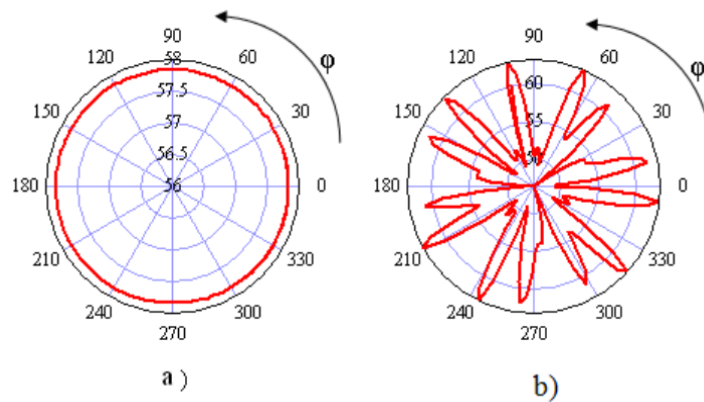


Figure 4 – Hodograph of AM moment in terms of ideal (a) and poor-quality (b) power supply in steady-state mode.

Figure 4 illustrates the hodograph of the electromagnetic torque of an asynchronous motor operating in steady-state conditions under two different power supply scenarios: ideal (a) and poor-quality (b). The comparison of these two cases provides clear insight into the influence of power quality on motor performance.

In case (a), which corresponds to a symmetrical and purely sinusoidal power supply, the hodograph takes the form of an almost perfect circle. This indicates that the electromagnetic torque remains nearly constant as the angular position  $\varphi$  changes. Based on the scale presented in the diagram, the torque varies within a narrow range of approximately 57 to 58 N·m, with an average value close to

57.5 N·m. The amplitude of torque pulsations does not exceed 1 N·m, which corresponds to less than 2% of the nominal value. Such behavior reflects a stable operating regime, where the rotating magnetic field is uniform and no significant harmonic components are present. As a result, the motor operates smoothly, with minimal vibration, reduced losses, and optimal efficiency.

In contrast, case (b) demonstrates the motor behavior under distorted and asymmetric voltage conditions. The hodograph in this case deviates significantly from a circular shape and instead exhibits a pronounced star-like pattern with multiple peaks and troughs. This distortion indicates strong fluctuations in the electromagnetic torque. The torque values now vary approximately between 54–55 N·m and 60 N·m, resulting in a pulsation amplitude of about 5–6 N·m. In relative terms, this corresponds to fluctuations on the order of 8–10% of the average torque value.

The presence of multiple local maxima in the hodograph suggests the influence of higher-order harmonics, such as the 5th and 7th harmonics, which are typical in systems with nonlinear loads. Additionally, the irregular shape reflects phase asymmetry in the supply voltage. These factors lead to non-uniform electromagnetic interactions within the motor, causing torque ripple, increased mechanical vibrations, acoustic noise, and additional thermal stress.

Thus, the comparison of the two diagrams clearly demonstrates that even if the average torque remains approximately the same in both cases, the quality of power supply has a decisive impact on the stability of torque production. Under poor-quality power conditions, significant torque oscillations arise, which negatively affect the mechanical integrity, efficiency, and service life of the asynchronous motor.

Figure 5 illustrates the rotor speed dynamics under ideal and distorted supply conditions. During startup, both cases reach near-synchronous speed ( $\approx 105$  rad/s); however, the distorted supply introduces additional oscillations with an amplitude of approximately 1–2%.

At the moment of load application ( $t \approx 0.6$  s), the rotor speed decreases from  $\approx 105$  rad/s to  $\approx 95$ – $97$  rad/s, corresponding to a drop of about 8–10%. Under distorted voltage, the steady-state speed is slightly higher (by  $\sim 1$ – $2\%$ ), but exhibits persistent pulsations with a magnitude of up to 2–3%.

These results indicate that while the average rotor speed is only marginally affected, power quality deterioration leads to a noticeable increase in speed oscillations and a reduction in dynamic stability of the drive system.

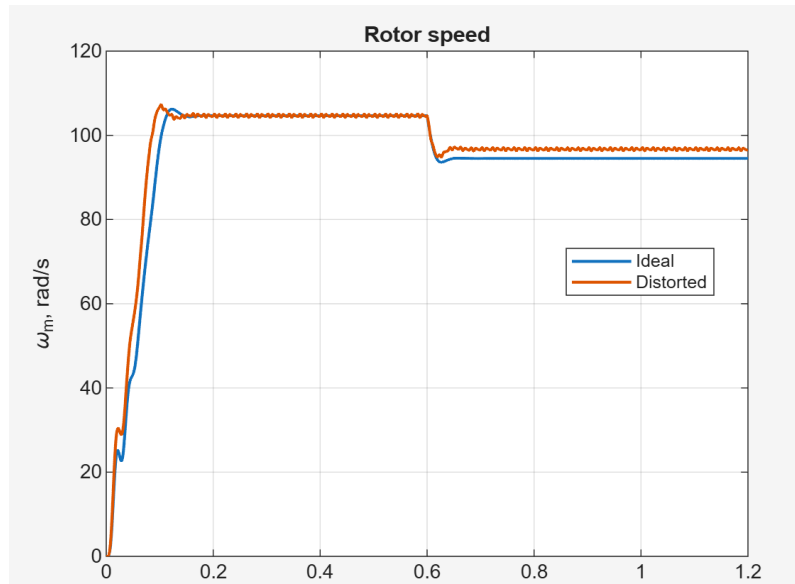


Figure 5 –Rotor speed dynamics under ideal and distorted supply conditions with load disturbance

Fig. 6 presents the time-domain response of the electromagnetic torque under ideal and distorted voltage supply conditions. During the startup phase, the distorted supply leads to significantly higher torque peaks, reaching up to approximately 240 N·m, which is about 90–100% higher than in the ideal case.

In steady-state operation prior to load application, the torque under distorted conditions exhibits pronounced oscillations with an amplitude of up to 15–20 N·m, while the ideal case remains relatively stable. Following load application ( $t \approx 0.6$  s), the average torque increases to approximately 70–80 N·m; however, torque pulsations persist with a magnitude of about 20–30%, indicating substantial electromagnetic instability.

These results demonstrate that voltage distortion significantly amplifies torque ripple and dynamic stress, which may lead to increased mechanical vibrations and accelerated wear of the drive system.

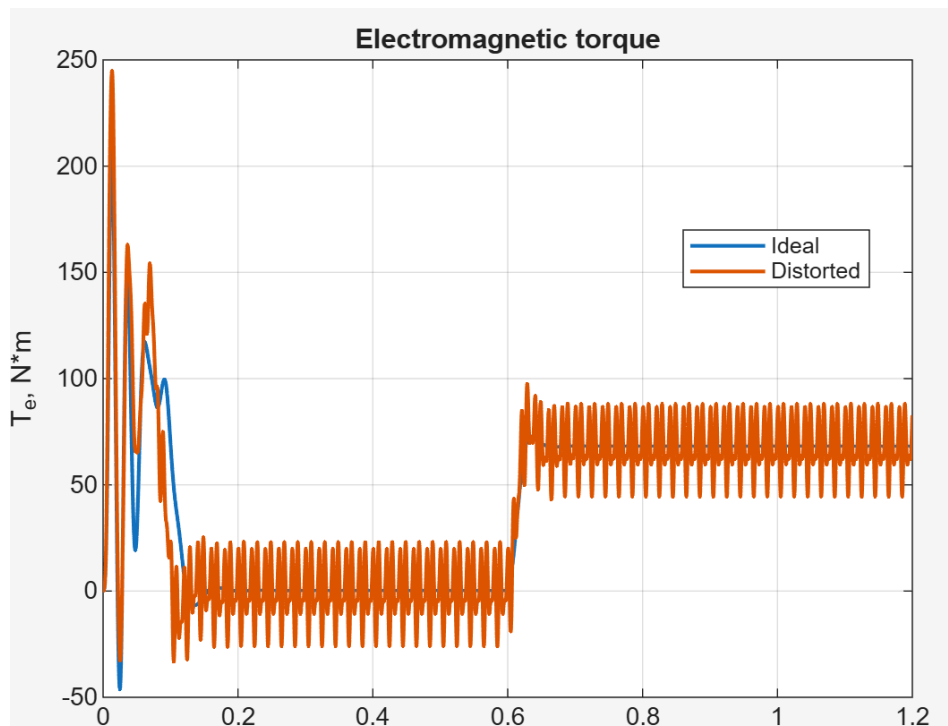


Figure 6 – Electromagnetic torque dynamics under ideal and distorted supply conditions with load disturbance

Fig. 7 presents the time-domain waveform of the stator current in phase A under ideal and distorted voltage supply conditions. During the startup phase, the distorted supply leads to significantly higher current peaks, reaching up to approximately 70–75 A, which is about 60–80% higher than in the ideal case.

In the steady-state no-load regime, the current under ideal conditions remains nearly sinusoidal with low amplitude ( $\approx 5\text{--}7$  A), whereas the distorted supply introduces waveform deformation and additional harmonic components, resulting in visible distortion and increased ripple.

Following load application ( $t \approx 0.6$  s), the current amplitude increases to approximately 18–22 A in both cases; however, under distorted conditions, the waveform exhibits clear non-sinusoidal behavior with persistent oscillatory distortion. The amplitude variation increases by approximately 10–15%, indicating additional harmonic content and increased electromagnetic stress.

These results confirm that poor power quality leads to current waveform distortion, increased peak currents, and higher harmonic content, which contribute to additional losses and thermal loading of the motor.

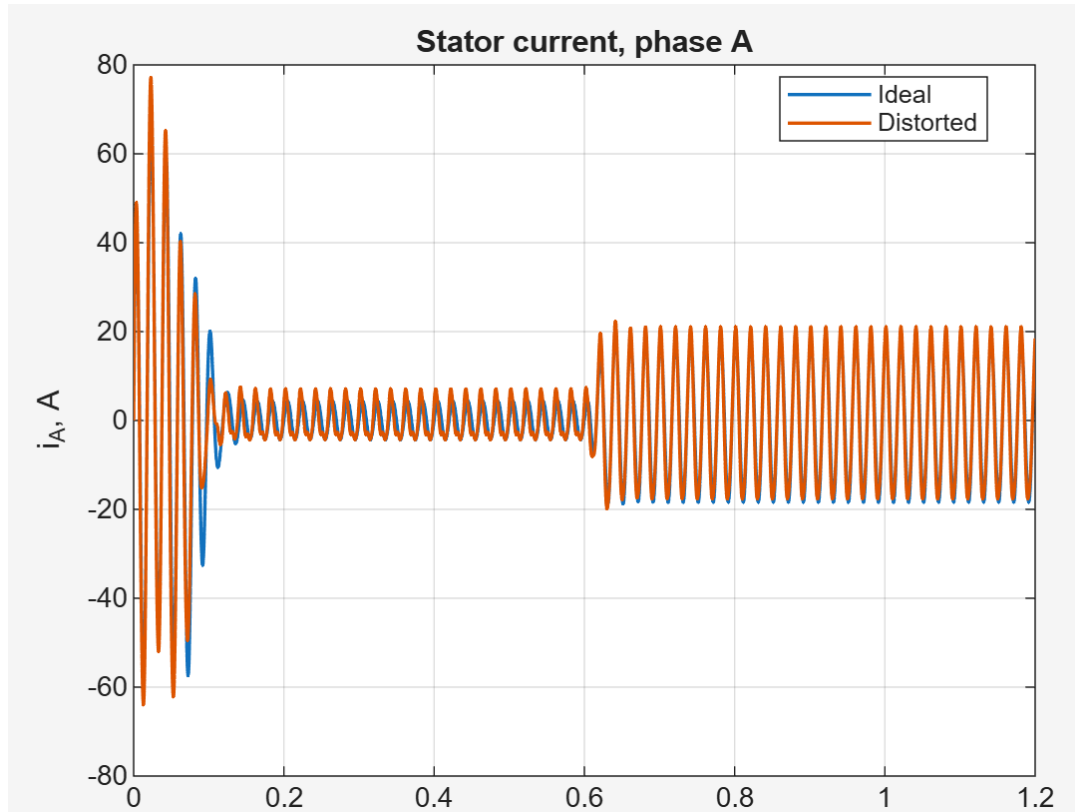


Figure 7– Stator phase A current waveform under ideal and distorted supply conditions with load disturbance

Analysis of the obtained power indices of AM operation represented in Table II confirms the fact that poor quality of supply voltage stipulates growth of all the types of losses; consequently there is a decrease in efficiency coefficient and power coefficient of a motor. In this connection, the paper does not consider increase in “heating” losses due to poor quality of supply voltage being determined by motor state and load character. That is the subject of another study.

Table 2

Power indices of am in terms of its poor-quality power supply

Parameters	Unit.	Sinusoidal power	Nonsinusoidal, asymmetric power
Electrical losses in a stator	W	491.30	498.30
Electrical losses in a rotor	W	652.210	661.510
Iron losses	W	89.210	90.10
Total losses	W	1235.00	1250.12
Coefficient of efficiency	%	81.41	81.22
Coefficient of power	p.u.	0.981	0.910

**Conclusions.** This study presents the development and validation of a dynamic electromagnetic model of a three-phase squirrel-cage asynchronous motor operating under conditions of degraded power quality, including voltage asymmetry and nonsinusoidal distortion. The model is based on space-time complexes (generalized vectors) and extended Park–Gorev equations, with nonlinear effects—such as magnetic saturation—accounted for through a polynomial dependence of mutual inductance on magnetizing current.

Simulation was performed for an MTKH 112-6 motor rated at 5.3 kW under two scenarios: ideal sinusoidal supply and distorted, asymmetric voltage conditions. The latter included phase voltage deviations of 11.2% (phase A), 18.8% (phase B), and 1.0% (phase C), as well as harmonic components up to the 10th order.

The results clearly demonstrate the negative impact of poor power quality on motor performance. Stator losses increased from 491.3 W to 498.3 W, while rotor losses rose from 652.2 W to 661.5 W. Iron losses also showed a slight increase from 89.2 W to 90 W. As a result, total losses grew from 1235 W to 1250 W, indicating additional energy dissipation and thermal stress.

This degradation affected efficiency, which decreased from 81.4% to 81.2%. More significantly, the power factor dropped from 0.98 to 0.90, reflecting reduced energy utilization and an increase in reactive power consumption. These findings confirm that even moderate voltage distortion and asymmetry lead to measurable performance deterioration.

Additionally, torque pulsations and waveform distortions in stator and rotor currents were observed, confirming increased electromagnetic stress under non-ideal conditions. The simulation results showed strong agreement with experimental data, with a relative RMS error below 4%, demonstrating the reliability of the proposed model.

The study emphasizes the importance of incorporating power quality indices into motor modeling, especially in industrial applications where operating conditions are far from ideal. Traditional models assuming perfect supply conditions fail to capture real losses and performance deviations.

Future work will focus on extending the model to include stochastic variations in power quality, enabling predictive analysis and supporting advanced diagnostics and maintenance strategies.

In conclusion, the developed model provides an effective tool for analyzing asynchronous motor performance under realistic supply conditions. Its applicability to both steady-state and transient режимs makes it valuable for design, control, and optimization tasks in modern industrial energy systems.

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**ДИНАМІЧНЕ МОДЕЛЮВАННЯ РОБОЧИХ ХАРАКТЕРИСТИК  
АСИНХРОННОГО ДВИГУНА ЗА УМОВ ПОГІРШЕННЯ ЯКОСТІ  
ЕЛЕКТРОЕНЕРГІЇ**

***Анотація.** У статті представлено динамічну електромагнітну модель трифазного асинхронного двигуна з короткозамкненим ротором, розроблену для моделювання його роботи в умовах реальних порушень якості електроенергії. Актуальність дослідження зумовлена зростаючим впливом проблем електромагнітної сумісності та енергетичних втрат у промислових системах, що працюють за умов асиметрії напруги та гармонічних спотворень - характерних для мереж із нелінійними навантаженнями, такими як зварювальне обладнання, дугові печі та частотні перетворювачі.*

*Традиційні моделі двигунів, які базуються на припущенні ідеальних умов живлення, не забезпечують достатньої точності для прогнозування погіршення характеристик за наявності таких спотворень. Для подолання цього обмеження запропонована модель побудована на основі просторово-часових комплексів та розширених рівнянь Парка–Горєва. Ключовою особливістю є врахування насичення магнітопроводу, змодельованого через поліноміальну залежність взаємної індуктивності від намагнічувального струму, що дозволяє більш точно описувати роботу двигуна в умовах високих навантажень та несиметрії.*

*Модель була апробована на асинхронному двигуні МТКН 112-6 потужністю 5,3 кВт у двох режимах: при ідеальній синусоїдальній нарузі та при спотвореному асиметричному живленні з гармоніками до 10-го порядку. Результати показали, що спотворення напруги призводить до зростання втрат у статорі (з 491,3 Вт до 498,3 Вт) і роторі (з 652,2 Вт до 661,5 Вт), зниження ККД (з 81,4% до 81,2%) та суттєвого зменшення коефіцієнта потужності (з 0,98 до 0,90). Крім того, спотворення форм струмів і пульсації моменту підтвердили підвищене електромагнітне навантаження на двигун.*

*Отримані результати моделювання добре узгоджуються з експериментальними даними ( $RMSE < 4\%$ ), що підтверджує надійність і практичну цінність запропонованої моделі для задач діагностики, прогнозного обслуговування, цифрових двійників та навчального моделювання. На відміну від традиційного*

гармонічного аналізу на основі перетворення Фур’є, використання просторово-часових комплексів дозволяє комплексно описувати як усталені, так і перехідні режими без необхідності розкладання на окремі гармоніки.

Дане дослідження робить внесок у розвиток енергоефективних та інтелектуальних промислових систем. Подальші дослідження будуть спрямовані на впровадження стохастичних моделей для врахування динамічних змін якості електроенергії, що дозволить реалізувати прогнозне керування та підтримати розвиток автоматизації в рамках концепції Industry 4.0.

**Ключові слова:** асинхронний двигун, якість електроенергії, динамічна модель, асиметрія напруги, гармонічні спотворення, електромагнітне моделювання, ефективність.

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