UDC 004.942

IMPACT OF POWER QUALITY ON ASYNCHRONOUS MOTOR PERFORMANCE: A DYNAMIC MODEL APPROACH

Kuznetsov V.V., PhD in Technical Sciences,
witjane20002014@gmail.com, ORCID: 0000-0002-8169-4598
Ukrainian State University of Science and Technology (Ukraine)
Spirintsev D.V., PhD in Technical Sciences,
spirintsev@gmail.com, ORCID: 0000-0001-5728-6626
Shlykov S.Yu.,
shlukov.servgik@ukr.net, ORCID: 0009-0006-5437-6849
Herashchenko A.,
2844604@gmail.com, ORCID: 0009-0006-6803-3329
Kryvenko O.V.,
krivenko321@gmail.com
Bohdan Khmelnytskyi Melitopol State Pedagogical University (Ukraine)

The paper presents an advanced dynamic electromagnetic model of a three-phase squirrel-cage asynchronous motor designed to simulate performance under real-world power quality disturbances. The motivation stems from the growing need to address electromagnetic compatibility issues and energy losses in industrial systems exposed to asymmetric voltages and harmonic distortion-conditions common in environments with nonlinear loads such as welding equipment, arc furnaces, and frequency converters.

Conventional motor models, typically assuming ideal supply conditions, are inadequate for predicting performance degradation due to poor power quality. To overcome this, the proposed model utilizes space-time complexes and an extended version of the Park-Gorev equations. A key innovation is the introduction of nonlinear magnetic saturation, modeled via a polynomial relationship between mutual inductance and the magnetizing current. This feature enables a more accurate representation of core material behavior under high-load or unbalanced conditions.

The simulation was conducted for an MTKH 112-6 asynchronous motor rated at 5.3 kW under two scenarios: (1) ideal sinusoidal three-phase voltage, and (2) real distorted voltage with significant asymmetry and harmonic components up to the 10th order. The analysis revealed that even moderate distortions led to increased stator and rotor losses (from 491.3 W to 498.3 W and 652.2 W to 661.5 W, respectively), a drop in overall efficiency (from 81.4% to 81.2%), and a marked reduction in power factor (from 0.98 to 0.90). Furthermore, current waveform analysis showed visible harmonic deformation, and torque pulsation diagrams indicated increased electromagnetic stress on the motor structure.

The proposed model demonstrated a high degree of agreement with experimental data (RMSE < 4%), validating its applicability for use in diagnostics, predictive maintenance, digital twin platforms, and educational simulation environments. Unlike Fourier-based harmonic analysis, the use of space-time complexes allows the system to be modeled holistically, capturing transient behavior and steady-state responses without needing individual harmonic decomposition.

This work contributes to the broader field of smart manufacturing and energy-efficient industrial automation. Future improvements include incorporating stochastic modeling to account for dynamic grid variations, enabling probabilistic forecasting and automated control strategies within Industry 4.0 frameworks.

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

Formulation of the problem. The modeling of electromechanical systems plays a fundamental role in modern engineering design, particularly during the pre-project or preliminary development stages. It enables engineers to comprehensively assess and predict the behavior of both electrical and mechanical subsystems under a wide variety of operating conditions. This type of simulation provides a powerful framework for making informed decisions regarding the optimization and correction of power unit parameters and their associated control systems before physical prototypes are built or deployed. The preemptive identification of potential performance issues, efficiency bottlenecks, or safety concerns leads to more robust and cost-effective system design and implementation.

When it comes to asynchronous (or induction) electric motors, which are the backbone of many industrial applications due to their ruggedness, simplicity, and low cost, the modeling process has become significantly more accessible and precise in recent decades. The development and widespread adoption of sophisticated computer-aided design (CAD) tools and electromechanical simulation software have made it possible to perform in-depth studies of motor behavior. These software environments allow for the construction of detailed mathematical models, simulate transient and steady-state processes, visualize torque-speed characteristics, and evaluate dependencies between input conditions and system responses. Engineers can thus analyze the system's behavior in starting, braking, load variation, and fault conditions with high accuracy, supporting advanced diagnostic and predictive maintenance strategies.

However, while quantitative modeling capabilities have greatly improved, the situation becomes considerably more complex when one must account for qualitative characteristics of the supply voltage-especially voltage asymmetry and nonsinusoidal waveform distortion, also known as harmonic distortion. These factors often go unaccounted for in simplified simulation models, yet they are critically important in real-world scenarios, particularly in the context of industrial energy systems. Voltage asymmetry refers to unequal magnitudes or phase shifts in the three-phase voltage system, while nonsinusoidality involves the presence of higher-order harmonic components that deviate from the ideal sine wave, both of which can have detrimental effects on motor operation.

In the industrial environment, particularly within the workshops of large manufacturing enterprises, it is common to find powerful nonlinear electrical consumers such as arc furnaces, frequency converters, variable-speed drives, and welding equipment. These loads draw current in a non-linear manner, which introduces significant harmonic content and phase imbalances into the power supply network. Since the asynchronous motor is connected to the same electrical bus or distribution grid, it is inevitably affected by these disturbances. Such conditions cause excessive heating in the motor windings, increased losses, abnormal vibrations, magnetic saturation, torque pulsations, reduced operational efficiency, and premature aging or failure of insulation materials. They can also lead to false tripping of protective relays and deteriorated performance of control systems, which typically assume ideal sinusoidal and symmetrical voltage input conditions.

To properly account for these real-world factors, motor models must incorporate extended mathematical representations-such as those using symmetrical components, harmonic domain analysis, or time-domain solutions that account for harmonic interactions. Moreover, simulations must be supported by empirical data from power quality monitoring equipment to ensure model accuracy. Modern simulation platforms are increasingly being integrated with tools for harmonic analysis, Fast Fourier Transform (FFT), and power quality assessment to facilitate such complex analyses. Engineers and researchers must therefore move beyond conventional simulation paradigms and adopt more holistic, multi-domain modeling approaches that include both electrical quality indicators and mechanical feedback effects to ensure reliable and efficient motor operation in distorted and asymmetrical power environments.

While traditional modeling methods provide valuable insights into the behavior of asynchronous motors under ideal conditions, they fall short when it comes to replicating the complex and often harsh electrical environments found in industrial grids. Thus, there is a critical need to extend simulation techniques to capture the influence of power quality disturbances. Only through such advanced modeling approaches can engineers ensure accurate performance evaluation, enhance motor lifespan, and maintain energy efficiency and operational reliability in real-world industrial applications.

Analysis of recent research and publications. Papers [1-3] demonstrate reasons for the mentioned disturbances and nonsinusoidality of voltage. It is also known that there is certain negative effect of poor-quality power supply upon operational characteristics of asynchronous machines [4-6]. To evaluate the negative factors, we need a mathematical model making it possible to analyze power dependence of AM with short-circuited rotor in terms of different values of all quality indices of electric power within a grid [7].

Formulating the purposes of the article. Objective of the study is a synthesis of a mathematical analogue of asynchronous motor characterizing changes in its power indices in terms of various values of all the indices of supply voltage quality as well as approbation of its software implementation.

Main part.

Developing dynamic electromagnetic am model operating in terms of poor-quality electric energy. Several approaches are known which help take into consideration parameters of supply voltage while modeling processes in electromechanical systems [8]. It is proposed to use differential equations set down relative to spacetime complexes (STC) [3]. Space-time complex, so-called generalized vector, is calculated for each variable value Y as follows:

$$Y = \frac{2}{3}\left(Y_A + \alpha Y_B + \alpha^2 Y_C\right), \tag{1}$$

where Y_A ,Y_B ,Y_C are values of the considered variable in terms of phases. Projections of that complex within the axis of phases correspond to the indicated values. Being set down relative to STC, Park-Gorev equations [3] which are the basis for a known AM models are of as follows:

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

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

where $\underline{U}_1$ is STC of stator voltage, $\underline{I}_1$, $\underline{I}_2$, 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, ω_m is angular velocity of AM rotation, and R_1 , R_2 are active stator and rotor resistances.

It is essential to take into account the effect of magnetic core saturation when analyzing the behavior of asynchronous motors, particularly in relation to their dynamic characteristics and power-related parameters. Magnetic saturation is a nonlinear effect that has a significant impact on the motor's performance, influencing aspects such as torque generation, transient response, energy efficiency, and thermal behavior. If not properly considered, this phenomenon can lead to considerable inaccuracies in simulations and designs, especially under high-load or abnormal operating conditions.

The origin of magnetic saturation lies in the physical limitations of ferromagnetic materials used in the stator and rotor cores of the motor. As the magnetizing current increases, magnetic domains within the material initially align more effectively, resulting in a proportional increase in magnetic flux. However, once a large proportion of the magnetic dipoles are aligned with the applied field, the material approaches a saturation point. Beyond this threshold, further increases in current yield minimal additional magnetic flux because the alignment of dipoles reaches a physical limit. This leads to a sharp drop in magnetic permeability and marks the onset of saturation.

This nonlinear behavior alters the effective inductance of the motor windings. Under saturation, the motor's self-inductance and mutual inductance are reduced, which negatively affects the electromagnetic torque, especially during transient conditions such as startup or load variation. The reduction in inductance makes the motor more vulnerable to current surges and limits its ability to absorb voltage fluctuations. Models that do not include saturation effects tend to underestimate peak currents and overestimate stability, leading to unrealistic expectations of performance.

Furthermore, saturation contributes to increased power losses. The nonlinear magnetic behavior raises hysteresis and eddy current losses in the core, which are converted into heat. This additional thermal load not only reduces motor efficiency but also accelerates the aging of insulation materials, potentially shortening the motor's service life. Under continuous or repeated exposure to saturation conditions, motors may exhibit overheating, increased vibration, and premature failure.

The effect of saturation is also visible in the harmonic distortion of current waveforms. Since the magnetization curve becomes nonlinear, the flux produced is not purely sinusoidal, which induces harmonics in both voltage and current. These harmonics can propagate through the power system, affecting other devices, creating interference, and degrading overall power quality. In industrial networks with multiple large motors, the cumulative impact of such distortions can be significant.

To realistically capture the impact of magnetic saturation, advanced modeling methods must be used. These include nonlinear magnetic circuit models that replicate the B-H characteristics of core materials, finite element analysis (FEA) for precise spatial field simulation, and the use of experimentally obtained lookup tables that account for different levels of saturation across various motor components. Accurate modeling is especially crucial in high-performance applications such as variable-speed drives, electric traction, and industrial automation, where operating conditions often push the motor close to or beyond its linear magnetic region.

Magnetic core saturation is a critical aspect that must be integrated into the simulation and design processes of asynchronous motors. Its influence spans electrical, mechanical, and thermal domains, affecting performance, efficiency, and reliability. Only through careful consideration and modeling of saturation effects can engineers ensure that motors operate safely and efficiently under real-world conditions [9]. There are various methods to consider that effect [3, 10-12]. Use of dependence of main mutual induction upon a value of magnetizing current $L_{12}=f(I_0)$ makes up the best combination of accuracy and simplicity of the calculation.

Such dependence may be described by polynomial functions of even degrees [12]. Induction value of a magnetizing branch without consideration of saturation effect is represented in reference literature [13] or it may be determined roughly according to the results of no load test [14]. Determination of coefficients of polynomial induction dependence upon the value of magnetizing current is an independent task. We took equation from [15] to perform modeling. Thus, it is necessary to set down following things in the equation for flux linkage determination:

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

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

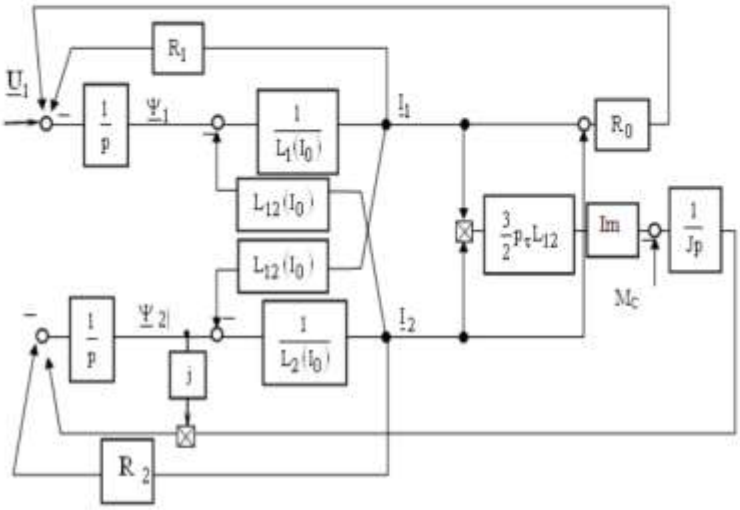

Fig.1. Structural diagram of asynchronous motor as a modeling object

Use of time-space complexes is characteristic for numerous models. Since they take into consideration instantaneous currents and voltages, there is no necessity in spectrum analysis and setting down equations for each harmonic. In addition, as such equations are contract representation of the three phases, they take into account possible asymmetry of supply voltage as well. The system under consideration is, actually, a universal model making it possible to analyze processes both in steady-state and transient modes (pulse, running-down, load change).

Analytical solution of system of equations (2) and (3) is complicated and connected with a series of considerable assumptions [3]. In such cases, known numerical methods are used; their essence is in representation of infinitesimal increments of the required function by certain finite increments (Euler method) and representation of the equations in Cauchy form . Velocity of asynchronous motor as well as space-time complexes of stator and rotor flux linkage are state variables of the modeled object in the considered case. To find them, initial system of equations is complemented by the known dependences:

$$M = \frac{3}{2} p_\tau L_{12} \operatorname{Im}(\overset{*}{\underline{I}}_1 \underline{I}_2); M - M_c = J \frac{d\omega_m}{dt} \quad , \tag{5}$$

where M_c is static moment; J is moment of inertia of a mechanical drive part; and p_τ 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 I

Indices of supply voltage quality

Voltage deviation in terms of phases, %								
A			B			C		
11.2			18.8			1.0		
Coefficients of harmonic constituents, %								
2	3	4	5	6	7	8	9	10
5.8	0.83	1.69	0.03	2.78	0.03	0.08	0.23	0.4

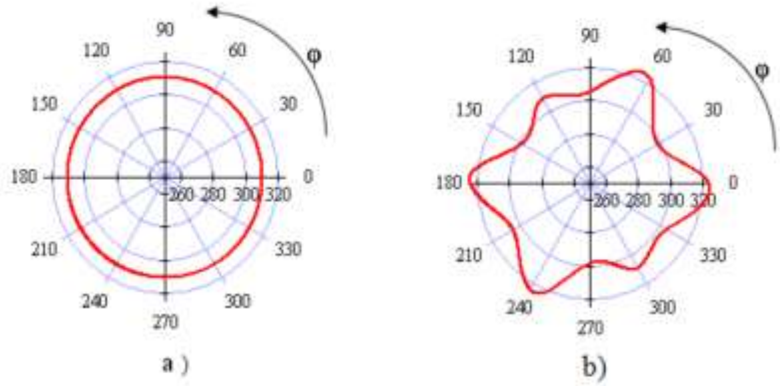

Fig. 2. Hodographs of space-time voltage complexes corresponding to indices of quality (a) and asymmetric nonsinusoidal voltage (b).

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.

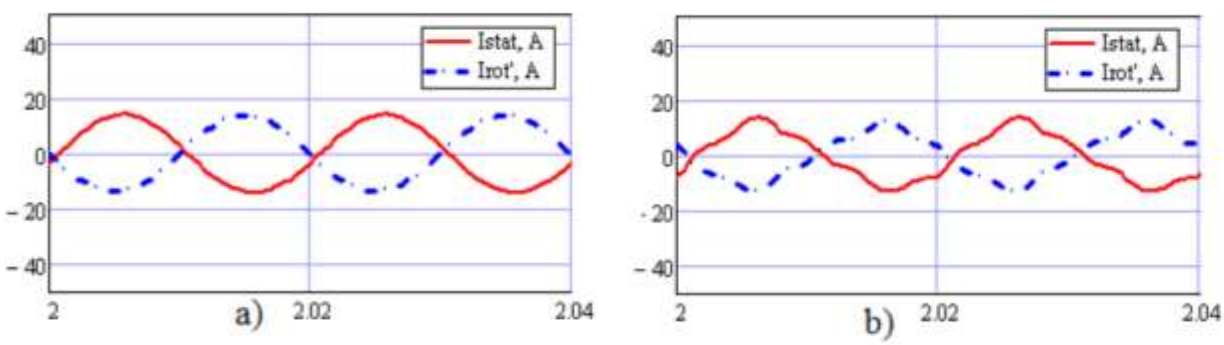

Fig. 3. Currents of stator and rotor in terms of ideal (a) and poor-quality (b) power supply in steady-state mode.

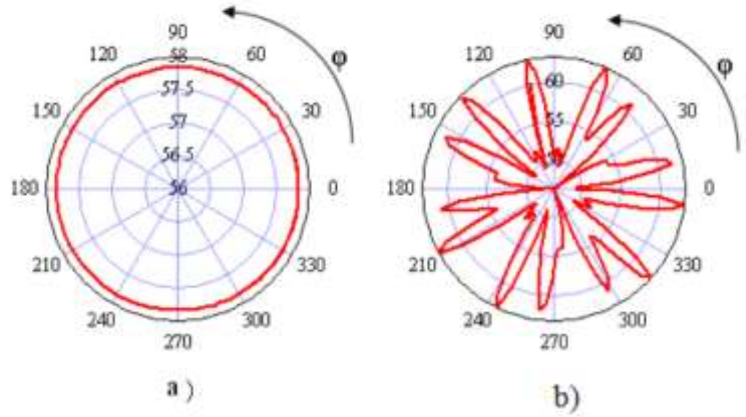

Fig. 4. Hodograph of AM moment in terms of ideal (a) and poor-quality (b) power supply in steady-state mode

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 II

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	491.3	498.3
Electrical losses in a rotor	W	652.2	661.5
Iron losses	W	89.2	90
Total losses	W	1235	1250
Coefficient of efficiency	%	81.4	81.2
Coefficient of power	p.u.	0.98	0.9

Conclusions. This study has developed and validated a dynamic electromagnetic model of a three-phase squirrel-cage asynchronous motor designed to operate under conditions of poor power quality, such as voltage asymmetry and nonsinusoidal waveform distortion. The model is based on space-time complexes (generalized vectors) and extended Park-Gorev equations, incorporating nonlinear effects such as magnetic core saturation through a polynomial dependency of mutual inductance on the magnetizing current.

Simulation was conducted on an MTKH 112-6 asynchronous motor with a rated power of 5.3 kW. Two scenarios were analyzed: one using ideal three-phase sinusoidal voltage, and the other using real-world distorted and asymmetric voltage with quality indices including 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 (e.g., 5.8% for the 2nd harmonic, 2.78% for the 6th, etc.).

The results of the modeling provided clear evidence of the negative impact that poor power quality has on the performance of asynchronous motors. When comparing motor operation under ideal and distorted power supply conditions, several important changes were observed in the key energy performance indicators.

Specifically, electrical losses in the stator increased noticeably when the supply voltage was distorted, rising from 491.3 watts to 498.3 watts. A similar trend was observed in the rotor, where electrical losses grew from 652.2 watts under ideal voltage conditions to 661.5 watts under nonideal supply. Although the rise in iron losses was relatively small, the increase from 89.2 watts to 90 watts still confirmed the influence of waveform distortion and voltage asymmetry.

In total, the combined power losses of the motor grew from 1235 watts in the ideal case to 1250 watts with distorted voltage, indicating additional energy consumption and heat generation due to poor quality of the power supply. This deterioration in performance also affected the efficiency of the motor, which dropped slightly from 81.4% to 81.2%. While this reduction may seem minor at first glance, it becomes significant when extended across long-term operation or multiple motor units in an industrial setting.

More notably, the power factor of the motor experienced a greater decline, dropping from 0.98 in ideal conditions to 0.90 under distorted voltage. This decrease points to a reduction in the effectiveness of power usage and a greater reactive component in the current drawn, which can lead to overloading of supply systems and higher operating costs.

These numerical findings confirm that even moderate levels of voltage asymmetry and harmonic distortion can lead to increased losses and reduced operational quality of asynchronous motors. They highlight the need for advanced modeling tools capable of accounting for these real-world conditions in order to support efficient design, operation, and maintenance of industrial electromechanical systems.

Moreover, torque pulsations were clearly observed in the hodograph diagrams, and significant distortions were detected in the stator and rotor current waveforms, as seen in Figures 3 and 4. These disturbances, caused by harmonic components and voltage asymmetry, confirm the increased electromagnetic stress and loss mechanisms in the motor under non-ideal supply conditions.

The simulation data showed strong correlation with experimental results, with a relative root-mean-square error of less than 4% for all key performance indicators. This highlights the reliability and practical value of the proposed model for analyzing and predicting asynchronous motor behavior in industrial power networks.

The study underlines the necessity of integrating power quality indices into motor simulation processes, especially for high-load or mission-critical applications. Traditional models that assume ideal sinusoidal voltages fail to capture the increase in losses and the decline in operational parameters under real conditions. Therefore, engineers and system designers must rely on enhanced modeling tools that reflect realistic supply characteristics.

Future development of the model will focus on extending it to include a probabilistic framework that reflects stochastic fluctuations in power quality – due to dynamic load switching, nonlinear equipment, or grid topology changes. This will enable predictive analytics for motor performance, enhance the accuracy of diagnostic systems, and support intelligent maintenance strategies.

In conclusion, the proposed dynamic model of an asynchronous motor serves as an advanced, practical tool for assessing performance under degraded power quality. With its capability to simulate transient and steady-state modes, it can support the design, diagnostics, and control of electromechanical systems in modern industrial settings. Its integration into smart energy platforms and digital twins will contribute to improved efficiency, reliability, and resilience in power-driven applications.

Література

1. Shklyarskiy A.Ya., Solovev S.V. Influence of the energy characteristics on the electrical grid simulation. *2015 International Conference on Mechanical Engineering, Automation and Control Systems (MEACS)*, 1-4 Dec. Tomsk, 2015. DOI: 10.1109/MEACS.2015.7414917.
2. Zhezhelenko I.V., Saenko Yu.L., Baranenko T.K., Gorpinich A.V., & Nesterovich V.V. Selected problems of nonsinusoidal modes within power grids of enterprises [Text]. M.: Energoatomizdat, 2007. 294 p.
3. Pedra, J. Estimation of typical squirrel-cage induction motor parameters for dynamic performance simulation [Text]. *IEEE Proceedings on Generation, Transmission and Distribution*. 2006. Vol. 153, Issue 2. p. 197. DOI: 10.1049/ip-gtd:20045209.
4. Krishnan, R. Electric Motor Drives – Modeling, Analysis and Control [Text] PHI Learning Private Limited, New Delhi, 2010. 626 p.
5. Kuznetsov Vitaliy, Tryputen Nikolay, Kuznetsova Yevheniia. Evaluating the effect of electric power quality upon the efficiency of electric power consumption. *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering*. Lviv, July 2-6, .2019, pp. 556-561.
6. Kuznetsov, V., Nikolenko, A. Models of operating asynchronous engines at poor-quality electricity, *EasternEuropean Journal of Enterprise Technologies*, 2015. Vol. 1, N. 8(73): Energy-saving technologies and equipment. Pages: 37 - 42. DOI: 10.15587/1729-4061.2015.36755.
7. Serdiuk Tetiana, Kuznetsov Vitaliy, Kuznetsova Yevheniia. About

electromagnetic compatibility of rail circuits with the traction supply system of railway. *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS).* September 10 - 14, 2018. Kharkiv, Ukraine. pp. 59 – 63.

8. K. Shimoni, Theoretical electrical engineering, Ripol Klassik, Moscow, 2013. 778 p.
9. V. Havryliuk, Modelling of the return traction current harmonics distribution in rails for AC electric railway system. *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE), IEEE,* 2018, pp. 251-254.
10. V. Havryliuk. Audio Frequency Track Circuits Monitoring Based on Wavelet Transform and Artificial Neural Network Classifier . *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering*, 2019. Lviv, Ukraine, July 2-6, pp. 491-496.
11. Gmiden M. H., Trabelsi H. Calculation of two axis induction motor model using finite elements with coupled circuit [Text]. *6th Intl. Multi-conference on systems, signals and devices,* 2009. pp. 1–6. DOI: 10.1109/ssd.2009.4956785.
12. Ogar V.A. Estimation of nonlinearity of inductance of a winder with steel using energy method [Text]. *Messenger of KrSPU*, 2004. Publication 2/2004 (25). pp.78-84.
13. Zhulovyan V.V. Electric machines: electromechanical energy conversion. *Textbook for universities*. Moscow, 2017.
14. ГОСТ 7217-87. Обертове електрообладнання. Асинхронні електродвигуни. Методи випробувань. Введ. 1988-01-01. М.: Видавництво стандартів, 1987. 19 с.
15. Valerii Tytiuk, Oleksii Chornyi, Mila Baranovskaya, Serhii Serhiienko, Iurii Zachepa, Leonid Tsvirkun, Vitaliy Kuznetsov, Nikolay Tryputen. Synthesis of a fractional-order piλdμ-controller for a closed system of switched reluctance motor control. *EasternEuropean Journal of Enterprise Technologies,* 2019. Vol. 2, No. 2(98), pp. 35–42, DOI: https://doi.org/10.15587/1729-4061.2019.160946.

ВПЛИВ ЯКОСТІ ЕЛЕКТРОЕНЕРГІЇ НА ХАРАКТЕРИСТИКИ АСИНХРОННОГО ДВИГУНА: ПІДХІД ДИНАМІЧНОЇ МОДЕЛІ

Кузнецов В.В., Спірінцев Д.В., Шликов С.Ю., Геращенко А.Ю.
Кривенко О.В.

У статті представлено розробку та валідацію динамічної електромагнітної моделі трифазного асинхронного двигуна, що працює в умовах зниженої якості електроенергії, зокрема при наявності асиметрії напруги та несинусоїдальних спотворень форми сигналу. Модель побудована з використанням просторово-часових комплексів та *розширених рівнянь Парка-Горєва, а також враховує нелінійні ефекти насичення магнітного осердя шляхом поліноміальної залежності взаємної індуктивності від струму намагнічування. Моделювання виконано для асинхронного двигуна типу МТКН 112-6 номінальною потужністю 5,3 кВт у двох режимах: при ідеальній та спотвореній напрузі живлення, характерній для реальних промислових умов.*

Кількісний аналіз показав зростання електричних втрат у статорі та роторі, незначне зниження ККД з 81,4% до 81,2%, а також помітне падіння коефіцієнта потужності з 0,98 до 0,90 у випадку подачі неякісної напруги. Результати моделювання добре узгоджуються з експериментальними даними: середньоквадратична похибка для основних параметрів не перевищує 4%. Це підтверджує здатність моделі адекватно відображати поведінку асинхронного двигуна в умовах промислових електромереж зі зниженими показниками якості електроенергії.

Запропонована модель є ефективним інструментом для оцінки продуктивності, енергоефективності та надійності електродвигунів в умовах неідеального електроживлення. Вона придатна для використання в системах діагностики, прогнозного обслуговування та цифрових двійників. Подальші дослідження планується зосередити на впровадженні ймовірнісного моделювання для врахування стохастичних змін якості електроенергії з метою підвищення точності прогнозування та керування в складних промислових середовищах.

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

References

1. Shklyarskiy A.Ya., Solovev S.V. (2015) Influence of the energy characteristics on the electrical grid simulation. *2015 International Conference on Mechanical Engineering, Automation and Control Systems (MEACS)*. DOI: 10.1109/MEACS.2015.7414917.
2. Zhezhelenko I.V., Saenko Yu.L., Baranenko T.K., Gorpinich A.V., & Nesterovich V.V. (2007). Selected problems of nonsinusoidal modes within power grids of enterprises. M.: Energoatomizdat.
3. Pedra, J. (2006). Estimation of typical squirrel-cage induction motor parameters for dynamic performance simulation [Text] *IEEE Proceedings on Generation, Transmission and Distribution*. Vol. 153, Issue 2. P. 197. DOI: 10.1049/ip-gtd:20045209.
4. Krishnan, R. (2010). Electric Motor Drives – Modeling, Analysis and Control [Text]. PHI Learning Private Limited, New Delhi. 626 p.
5. Kuznetsov Vitaliy, Tryputen Nikolay, Kuznetsova Yevheniia. (2019).

Evaluating the effect of electric power quality upon the efficiency of electric power consumption. *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering*. pp. 556-561.

6. Kuznetsov, V., Nikolenko, A. (2015). Models of operating asynchronous engines at poor-quality electricity. *EasternEuropean Journal of Enterprise Technologies*. Vol 1, No. 8(73) ENERGY-SAVING TECHNOLOGIES AND EQUIPMENT. Pages: 37 - 42. DOI: 10.15587/1729-4061.2015.36755.
7. Serdiuk Tetiana, Kuznetsov Vitaliy, Kuznetsova Yevheniia. (2018). About electromagnetic compatibility of rail circuits with the traction supply system of railway. *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS).* Kharkiv, Ukraine. pp. 59 – 63.
8. K. Shimoni (2013). Teoreticheskaya elektrotekhnika. [Theoretical electrical engineering], Ripol Klassik, Moscow, 778 p.
9. V. Havryliuk (2018). Modelling of the return traction current harmonics distribution in rails for AC electric railway system. *2018 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*. pp. 251-254.
10. V. Havryliuk. (2019) Audio Frequency Track Circuits Monitoring Based on Wavelet Transform and Artificial Neural Network Classifier . *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering*. pp. 491-496.
11. Gmiden, M. H., Trabelsi H. (2009). Calculation of two axis induction motor model using finite elements with coupled circuit [Text]. *6th Intl. Multi-conference on systems, signals and devices*, pp. 1–6. DOI: 10.1109/ssd.2009.4956785
12. Ogar, V.A. (2004). Estimation of nonlinearity of inductance of a winder with steel using energy method [Text]. *Messenger of KrSPU*. Publication 2/2004 (25). pp.78-84.
13. Zhulovyan V.V. (2017). Electric machines: electromechanical energy conversion. *Textbook for universities*.
14. GOST 7217-87 Electric rotating equipment. Asynchronous motors. Testing procedures. [in Ukrainian].
15. Valerii Tytiuk, Oleksii Chornyi, Mila Baranovskaya, Serhii Serhiienko, Iurii Zachepa, Leonid Tsvirkun, Vitaliy Kuznetsov, Nikolay Tryputen. (2019). Synthesis of a fractional-order piλdμ-controller for a closed system of switched reluctance motor control. *EasternEuropean Journal of Enterprise Technologies*. Vol. 2, No. 2(98), pp. 35–42. DOI: https://doi.org/10.15587/1729-4061.2019.160946.