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FEATURES OF THE INFLUENCE OF THE TECHNICAL PARAMETERS OF ASYNCHRONOUS MOTOR ON THE FORMATION OF IT'S THREE-PHASE STATOR CURRENT SYSTEM

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In recent decades, there has been a growing trend towards the increasing role of automated electric drives implemented based on asynchronous motors. This trend is driven by several objective factors, among which the main ones are the development of mathematical models of asynchronous motors, leading to increased accuracy and functional capabilities of their control systems, and active advancement in power semiconductor technology, resulting in improved efficiency and reduced cost of power frequency converters.

It is worth noting that a consequence of modern technical progress is the increase in complexity, cost, and technological sophistication of industrial equipment, thus leading to potential losses accompanied by its malfunction during operation. Another trend in the development of industry, both in Ukraine and in most industrially advanced countries, is the increase in the quantity of electrical equipment that has reached its nominal service life. Since there is an inverse proportional relationship between reliability and operating time of rotating electric machines, it is quite logical and evident that this leads to the growing relevance of building highly efficient systems for their diagnostics.

The article justifies the expediency of applying current-based diagnostic methods for asynchronous motors, which do not require intervention in the construction of the electric machine, allowing simplification of the design of the diagnostic system and reducing capital costs for its construction. It also theoretically substantiates the functional relationship between the technological parameters of an asynchronous motor and the frequencies of the components of the current signal of its stator circuit, on which their influence will manifest, which in perspective will allow identifying abnormal deviations from the corresponding technological parameters by monitoring the harmonic components of the stator current.

Key words: *asynchronous motor, diagnostics, stator current, harmonic components, magnetic field, disturbance, technological parameters.*

F. 15. Fig. 1. Ref. 13.

1. Problem formulation

The magnetic field that arises in the stator of an ideal asynchronous motor (AM) has a completely symmetric shape. However, in the operation of a real AM, the formation of disturbances in the electromagnetic field inevitably occurs, due to deviations in its design parameters both due to inaccuracies in its manufacture and due to defective degradation of structural nodes [1]. It is obvious that the presence of disturbances, which lead to deformation of the AM magnetic field, will inevitably manifest through the increase in nonlinearity of the stator resistance and its asymmetry. This, in turn, will cause an increase in the amplitudes of both higher harmonics in each phase separately and the amplitude of the direct and reverse sequence of the three-phase stator current system [2, 3].

It should be noted that the stator current is a convenient signal for monitoring. Therefore, considering the presence of a functional dependence between the characteristics of the three-phase stator current system of the AM and its current technical condition, it is obvious that the study of the features of such a functional relationship is a relevant scientific and applied task, the solution of which can become a significant impetus for the further development of promising diagnostic systems for rotating electrical machines.

2. Analysis of recent research and publications

In most modern automatic control systems for asynchronous drives, functions for measuring currents and voltages of the stator circuit of electric machines are already provided [4, 5]. However, in the absence of such a measurement system, its practical implementation will not require intervention in the construction of the electric machine. These circumstances, in the case of using stator current parameters as diagnostic indicators, will allow for significant simplification of the design of the diagnostic system and reduce the capital costs for its construction in many cases, thereby increasing the feasibility of such a diagnostic method [6]. For instance, one possible example of practical implementation of a measurement system for currents and voltages of the stator circuit of the AM is shown in Fig. 1.

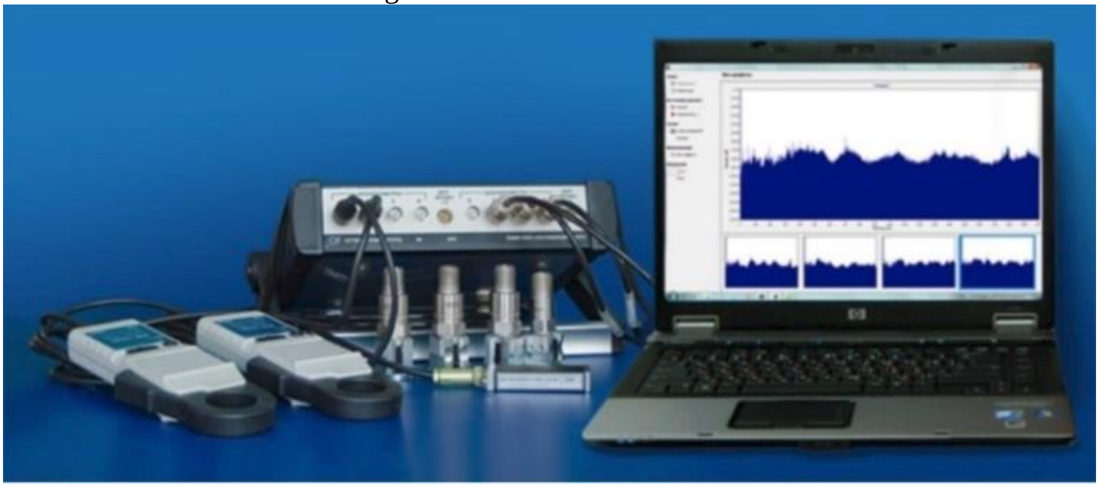

Fig. 1. An example of the implementation of the measuring system of currents and voltages of the stator circuit AM

At present, the widespread use of such an approach is significantly limited by the absence of high-precision mathematical models that would describe the influence of deviations in the technological parameters of AMs, including those caused by the development of the most probable defects, on the parameters of the three-phase stator current system. Therefore, considering the aforementioned, the relevance of further research aimed at obtaining such mathematical dependencies can be emphasized.

In alternating current motors, the electromagnetic forces applied to their structural nodes have a frequency twice that of the magnetic field frequency, as the latter is proportional to the magnitude of the magnetic flux modulation [7]. That is:

$$f_{EM} = 2 f_1, \tag{1}$$

where f_1 – power supply frequency.

In a symmetric winding of the rotor, electromagnetic forces do not have variable components but only generate the working torque. However, if the stator currents are asymmetric, pulsating components of the electromagnetic torque are formed with a double slip frequency:

$$f_{2s} = f_1 \cdot 2s, \tag{2}$$

where s – AM sliding, which can be defined as:

$$s = \frac{f_1 - f_r}{f_1}, \tag{3}$$

where f_r – rotation frequency of the AM rotor.

In turn, mechanical vibrations in AM, caused by electromagnetic forces, will also occur at twice the frequency of the mains. Therefore, the force of electromagnetic influence between each pair of current-carrying elements will also have a double frequency relative to the mains frequency:

$$f_{ЕД} = 2 f_1, \tag{4}$$

In turn, in the case of an asymmetric stator field, when the magnetic field has a reverse component, a weak variable electromagnetic force appears, and accordingly, a torque with a frequency:

$$f_{EM} = 2 f_1, \tag{5}$$

In this case, as a rule, an increase in the amplitude of the reverse sequence occurs either due to asymmetry in the stator windings or due to asymmetry in the power supply network. In the latter case, corresponding distortions should also be expected in the three-phase voltage system at the terminal clamps of the investigated motor [8].

The next most significant in terms of amplitude are the oscillating forces of electromagnetic nature acting at tooth frequencies, which are determined by the periodic alternation of ferromagnetic teeth and slots on the stator and rotor. The tooth frequency of the rotor can be determined by the following equation:

$$f_{zr} = f_r \cdot Z_2, \tag{6}$$

where f_r – rotor rotation frequency; Z_2 – the number of rotor teeth.

Accordingly, the stator tooth frequency:

$$f_{zs} = \frac{f_1 \cdot Z_1}{p}, \tag{7}$$

where Z_1 – the number of stator teeth; p – the number of pairs of poles.

The magnetic saturation of the active iron in the tooth zone of the rotor is characterized by the increase in radial vibrations of the machine at frequencies kf_1, which are multiples of the mains frequency [9].

The development of defects in AMs, caused by damage to mechanical and electrical components, leads to the emergence of additional vibrations, which in turn results in the appearance of additional higher harmonics in the magnetic field. As a consequence, there is an additional change in the spectral composition of the investigated currents.

3. The purpose of the article

The purpose of this study is to develop and justify effective current methods for diagnosing asynchronous electric motors, which allow identifying abnormal deviations of technological parameters without contact and without interfering with the design of the equipment.

4. Results of the researches

In real electric machines, in the air gap, in addition to the fundamental harmonic, there exists an infinite number of harmonics of the magnetic field. These harmonics have frequencies higher and lower than the fundamentals, which are referred to as higher harmonics and subharmonics, respectively. Higher harmonics differ from each other in amplitudes and frequencies, and they are conventionally divided into temporal and spatial harmonics.

Temporal harmonics are those arising in the air gap from the side of the machine terminals (from the network, shaft, and thermal output). Spatial harmonics are caused by the design features and nonlinear parameters of the machine [8].

Spatial harmonics of the field induce higher harmonics of electromagnetic forces (EMF) in the stator winding. To reduce these and consequently improve the shape of the EMF curve, measures such as shortening the step, skewing the slots, and distributing the winding across slots are applied so that the number of coils within a coil group is $q > 1$, etc.

Spatial harmonics arising from design features and nonlinear parameters of the machine significantly influence energy conversion processes in the air gap. In the case of a concentrically arranged rotor in the air gap and open slots in the stator and rotor with the numbers Z_s and Z_r and the number of pole pairs p, the most pronounced harmonics of field induction of the following orders exist [7, 9]:

- the main harmonic, which has p periods around the air gap circumference, forming a rotating field with induction:

$$B_1 = \frac{4}{\pi} \frac{F_1 \mu_0}{\delta} \lambda_0 \cos\left(\frac{\pi x}{\tau} - \omega_1 t\right), \tag{8}$$

where F_1 – amplitude of the magnetizing force of the main harmonic; τ – polar division; δ – air gap between stator and rotor, mm; λ_0 – constant component of air gap conductivity; ω_1 – cyclic frequency of the power supply network; x – projection of harmonic amplitude along the abscissa axis.

- harmonics of the order of stator tooth, arising as a result of variable magnetic conductivity, which forms a rotating field with induction:

$$B_{zs1}+B_{zs2}=\frac{4}{\pi}\frac{F_1\mu_0}{\delta}\lambda_{zs1}\cos\left((2m_1q-1)\frac{\pi x}{\tau}-\omega_1 t\right)+\lambda_{zs2}\cos\left((2m_1q-1)\frac{\pi x}{\tau}-\omega_1 t\right), \qquad (9)$$

where m_1 – the number of phases of the stator winding; q – the number of grooves per pole and phase of the winding; λ_{zs1}, λ_{zs2} – the relative amplitudes of the toothed harmonics of the stator air gap conductance;

- harmonics of the order determined by the number of phase zones forming rotating fields of the type:

$$B_{zr1}+B_{zr2}=\frac{4}{\pi}\frac{F_1\mu_0}{\delta}\lambda_{zs1}\cos\left((\frac{z_r}{p}-1)\frac{\pi x}{\tau}-\omega_1 t\right)+\lambda_{zs2}\cos\left((\frac{z_r}{p}-1)\frac{\pi x}{\tau}-\omega_1 t\right), \qquad (10)$$

where Z_r – the number of rotor grooves; ω_r – cyclic frequency of rotation of the rotor; λ_{zr1}, λ_{zr2} – relative amplitudes of toothed harmonics of rotor air gap conductance.

In addition, there are higher-order harmonics, which typically have smaller amplitudes and different combinatorial components. It is worth noting that the harmonic composition of the actual spectrum of the stator current of an AM is the result of electromagnetic phenomena, power supply conditions, and the specifics of the mechanical drive system. The spectrum of harmonic components of the current includes harmonics related to its design features [10]:

- higher-order harmonics of order 6c±1 are caused by other harmonics of the magnetically motive force (MMF) in the stator winding:

$$f_{MPC}=f_1(6c\pm1), \qquad (11)$$

where c = 1, 2, 3 … (whole numbers).

Harmonics are multiples of the 50 Hz frequency. Harmonics of order (6c+1) rotate in the same direction as the first-order harmonic, while harmonics of order (6c-1) rotate in the opposite direction [10]:

- tooth harmonics of the rotor caused by the presence of grooves in the rotor core:

$$f_{ЗГР}=\frac{k\cdot Z_r}{p}f_r\pm f_1, \qquad (12)$$

where Z_r – number of rotor grooves (number of rods).

- tooth harmonics of the stator caused by the presence of grooves in the stator core:

$$f_{ЗГС}=f_1\left(\frac{k\cdot Z_s}{p}\pm1\right), \qquad (13)$$

where k = 1, 2, 3 … (whole numbers); Z_s – the number of stator grooves; p – the number of pairs of poles.

A significant increase in the amplitude of tooth harmonics of the stator field occurs during the no-load operation of the AM, while relatively less occurs during nominal load [7].

- higher harmonics caused by a change in the mutual location of the grooves of the stator and rotor:

$$f_{ЗГС\_ЗГР}=f_1\left(\frac{k\cdot Z_s}{p}\pm\frac{k\cdot Z_r}{p}\pm1\right). \qquad (13)$$

As a rule, the amplitudes of tooth harmonics are significantly influenced by the ratio of the number of grooves on the stator and rotor. Some ratios are not permissible as they cause significant vibrations and noise [11, 12].

- higher harmonics due to core saturation:

$$f_{нас}=f_1(2k-1), \qquad (14)$$

In low-power AMs, the influence of these harmonics in the slip interval s = 0÷1 can be neglected due to their negligible contribution [10, 13].

- higher harmonics, characterized by the number of pole pairs, are caused by the interaction of saturation harmonics with the rotor winding:

$$f_{нас\_ОР}=f_1\left(p(2k-1)\pm k\cdot Z\right), \qquad (15)$$

- higher harmonics caused by the discreteness of the arrangement of bars in the closed-loop rotor winding:

$$f_{ОР}=f_1\left(\frac{k\cdot Z_r}{p}\pm1\right). \qquad (16)$$

- harmonics with frequencies dependent on the rotor rotation speed [11, 13]:

$$f_{rn}=\left|k\cdot f_1+n\cdot f_r\right|, \qquad (15)$$

where n = ±1, ±2, … (whole numbers).

It is necessary to take into account current harmonics, the frequencies of which are related to the third harmonic with respect to f_1 , which may arise due to the supply of stator windings with voltages containing the third harmonic. Another reason for their manifestation is saturation of the magnetic circuit. Diagnostic assessment of the motor using spectral analysis of currents requires identifying the largest number of harmonics and selecting those necessary for a correct fault assessment. When a fault occurs, the operating machine becomes a generator of additional harmonics with corresponding frequencies [10, 11].

Considering [9-11], the stator winding (with an integer number of slots per pole and phase) with magnetic and electrical symmetry of the motor acts as a filter for this frequency, passing only harmonics whose order satisfies the condition ($\nu = 6 \cdot c \pm 1$) та ($\nu = 1 \pm kZ_s/p$).

In the event of a fault, there is a disruption of the internal symmetry of the motor. In such a case, it is necessary to theoretically consider their impact on the operation mode. It is essential to identify harmonic components caused by bearing wear and inter-turn short circuits.

5. Conclusions

1. The application of current-based diagnostic methods for asynchronous motors is justified as they do not require intervention in the machine's construction. This allows simplification of the diagnostic system design and reduces capital costs for its implementation. Current-based methods, such as spectral analysis of currents, provide information about the machine's condition by measuring and analyzing electrical parameters reflecting mechanical status. This enables timely detection of anomalies and deviations in machine operation, facilitating planned maintenance and repair activities.

2. The theoretical justification of the functional relationship between the technological parameters of the asynchronous motor and the frequencies of the components of its stator current signal, where their influence manifests, will allow the identification of abnormal deviations from the respective technological parameters through monitoring of the harmonic components of the stator current.

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ОСОБЛИВОСТІ ВПЛИВУ ТЕХНІЧНИХ ПАРАМЕТРІВ АСИНХРОННОГО ДВИГУНА НА ФОРМУВАННЯ ТРИФАЗНОЇ СИСТЕМИ СТРУМУ СТАТОРА

Останніми десятиліттями усе активніше спостерігається тенденція до зростання ролі автоматизованих електроприводів, реалізованих на базі асинхронних електродвигунів. Це обумовлено рядом об'єктивних факторів, серед яких основними є розвиток математичних моделей асинхронних електродвигунів, що у свою чергу призвело до підвищення точності та функціональних можливостей систем їх керування, та активним розвитком силової напівпровідникової техніки, що у свою чергу обумовило підвищення ефективності та зменшення вартості силових частотних перетворювачів.

Варто відзначити і ту обставину, що наслідком сучасного технічного прогресу є зростання складності, вартості та технологічності виробничого обладнання, а отже, зростання потенційних втрат, що супроводжується його аварійною відмовою в процесі експлуатації. Ще однією тенденцією розвитку промисловості, як України, так і більшості промислово розвинутих країн світу, є збільшення кількості електрообладнання, яке відпрацювало свій номінальний термін служби. Оскільки між надійністю та часом напрацюванням обертових електричних машин існує обернено пропорційна залежність, то цілком логічним і очевидним наслідком цього є зростання актуальності побудови високоефективних систем їх діагностування.

У статті обґрунтовано доцільність застосування струмових методів діагностування асинхронних двигунів, як таких, що не передбачають необхідність втручання у конструкцію електричної машини, дозволяють спростити конструктивне виконання системи діагностування та знизити капітальні витрати на її побудову. А також теоретично обґрунтовано функціональний зв'язок між технологічними параметрами асинхронного двигуна та частотами складових струмового сигналу його статорного кола, на яких проявлятиметься їх вплив, що у перспективі дозволить ідентифікувати аномальні відхилення відповідних технологічних параметрів шляхом моніторингу гармонічних складових струму статора.

Ключові слова: *асинхронний двигун, діагностування, струм статора, гармонічні складові, магнітне полк, збурення, технологічні параметри.*

Ф. 15. Рис. 1. Літ. 13.

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