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FEATURES OF THE INFLUENCE OF A SHORT CIRCUIT OF THE STATOR WINDING OF AN INDUCTION MOTOR ON THE SPECTRAL COMPOSITION OF ITS STATOR CURRENT

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In recent decades, there has been a consistent trend towards the increasing role of automated electric drives based on induction motors. This is driven by objective factors, such as the development of high-precision mathematical models of induction motors, which have improved the accuracy and functionality of their control systems, as well as advancements in power semiconductor technologies that have enhanced efficiency and reduced the cost of frequency converters. These advancements in scientific and technical progress have led to an expansion of the application of induction motors in controlled electric drives under difficult starting conditions, which were traditionally implemented using direct current motors, as well as an increase in the number of electric drives with electric control types.

At the same time, modern technological progress has also resulted in increased complexity, cost, and technological demands of industrial equipment, which raises potential risks of emergency failures. Another common trend for Ukraine and many industrially developed countries is the growing number of electrical equipment that has reached the end of its nominal service life. Since there is an inverse relationship between the reliability and operating time of rotating electrical machines, this logically leads to an increased need for effective diagnostic systems.

The article theoretically proves the influence of interturn short circuits in the stator windings of an induction motor on the shape of its stator currents. It is shown that this diagnostic method has a sufficient degree of expressiveness, allowing for a high probability of identifying this type of defect among other types of damage to the induction electric machine. The justification for using the amplitude of the fundamental harmonic f_1 for diagnosing this type of defect is provided, along with the subsequent modulation of even harmonics at frequencies of $2f_1$ to $10f_1$. It is proposed to consider the current spectrum in a logarithmic scale of dB/Hz due to the presence of a dominant current component at the power supply frequency f_1.

Key words: *induction motors, diagnostics, short circuit, stator winding, asymmetry, harmonics.*
Eq. 8. Fig. 1. Ref. 10.

1. Problem formulation

During the operation of an ideal induction motor (IM), the stator magnetic field has a perfectly symmetrical structure. However, in real IMs, where actual physical parameters deviate from the ideal, this field inevitably becomes distorted [1]. Such deformation of the magnetic field, in turn, leads to changes in the parameters of the stator circuit (resistance, inductance, etc.) over time, resulting in the emergence of higher harmonics in the stator currents. It is important to note that different types and degrees of deviation of real parameters from the design will have unique characteristics, forming an individual current spectrum of the stator [2]. Since this spectrum is convenient for real-time monitoring, it can be concluded that current diagnostic methods have high potential for assessing the degree of defect development in the motor's design parameters.

According to the statistical analysis of the causes of failures in induction motors conducted by the company "VENTUS.UA" [3], stator winding short circuits account for over 20 % of emergency failures in medium-power induction motors. This indicates that short circuits in stator windings can be considered a highly probable defect during the operation of induction motors.

It is noteworthy that most modern automated control systems for induction motors already include functions for measuring currents and voltages in the stator circuit. If such a measuring system is absent in the motor control system, its technical implementation will not require changes to the design of the electric machine [4]. In particular, an example of such a monitoring system for current and voltage in the stator circuit of an induction motor is presented in Figure 1.

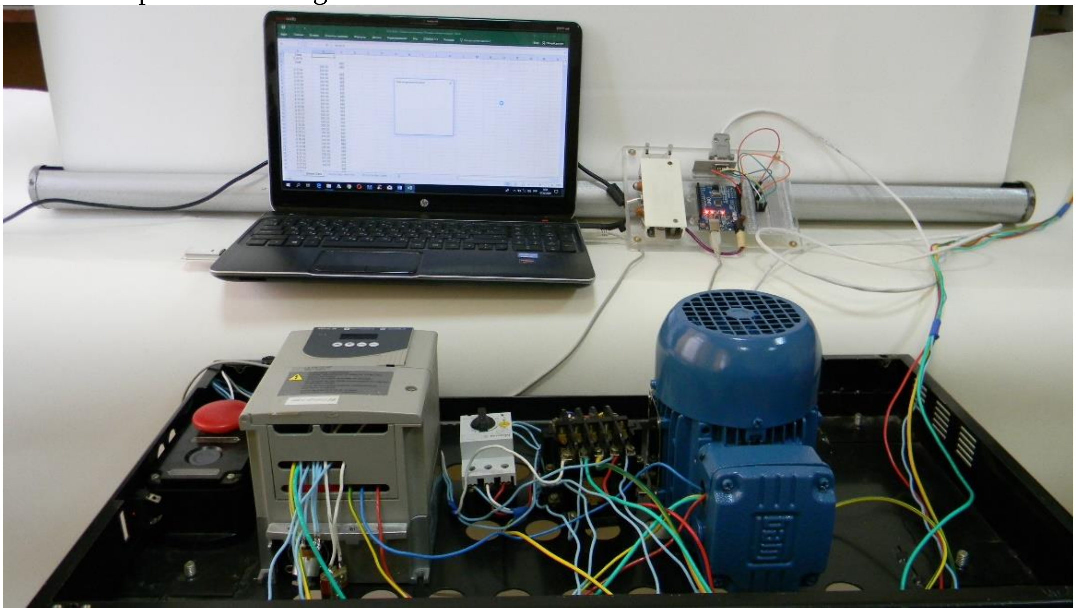

Fig. 1. Implementation of the current and voltage monitoring system of the stator circuit of an induction motor

This allows us to conclude that using stator current parameters for diagnosing the specified defect offers significant advantages compared to other diagnostic methods. However, the widespread application of this approach is currently limited by the lack of effective mathematical models that correlate the spectral composition of the stator current with the presence and severity of stator winding short circuits. Therefore, solving this scientific and practical problem holds great theoretical and practical significance.

2. Analysis of recent research and publications

In alternating current machines, the electromagnetic forces acting on their structural elements have a frequency that is twice that of the magnetic field. This is due to their proportionality to the magnitude of the magnetic flux [5]. That is:

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

where f_1 – power supply frequency.

In a symmetrical rotor winding, the electrodynamic forces do not have varying components and only generate a working torque. However, if the stator currents are asymmetric, this leads to the emergence of pulsating components of the electromagnetic torque with a double slip frequency.

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

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

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

where f_r – rotation frequency of the IM.

The mechanical vibrations in an induction motor, caused by electrodynamic forces, will also have a frequency that is twice that of the power supply frequency. Thus, the electrodynamic force of influence between each pair of current-carrying elements will also exhibit a double frequency relative to the supply frequency:

$$f_{ЕД} = 2 f_1, \tag{4}$$

In the case of an asymmetric stator field, where the magnetic field has a reverse component, a weak variable electrodynamic force arises, as well as a torque with a frequency of:

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

In such cases, an increase in the amplitude of the reverse sequence is typically observed either with stator winding asymmetry or with asymmetry in the power supply. In the latter case, the corresponding distortions can also be detected in the three-phase voltage system at the terminals of the machine being studied [6].

3. The purpose of the article

Development of a technique for diagnosing inter-turn short-circuits in the stator windings of asynchronous motors based on the analysis of the spectral composition of the stator currents to increase the reliability of the operation of electric machines and prevent emergency situations.

Research objectives:

- to theoretically substantiate the influence of inter-turn circuits in the stator windings on the spectral composition of the stator currents;
- investigate the characteristics of changes in the amplitudes of the fundamental harmonic (f_1) and modulated even harmonics ($2f_1 \div 10f_1$) depending on the presence of a defect;
- develop a mathematical model to estimate the relationship between the parameters of the stator currents and the degree of inter-turn short circuit development
- propose the use of the logarithmic scale of the current spectrum (dB/Hz) as a tool to improve real-time defect detection
- develop recommendations for the implementation of this technique in automated control systems of asynchronous motors without making constructive changes in their design.

These tasks are aimed at creating an effective diagnostic system to increase the reliability of asynchronous motors, especially in conditions of increased wear or difficult operating conditions.

4. Results of the researches

The operating mode of an induction motor with interturn short circuits is characterized by increased heating of the affected winding section. In this case, the development of the defect is quite intense.

When an IM operates with a symmetrical stator winding, the currents in all phases are nearly equal. However, an interturn short circuit in one of the stator phases leads to a reduction in the number of turns in that winding. With a decrease in the number of turns, the corresponding phase current increases [7].

Winding asymmetry in the stator results in a decrease in the sinusoidal distribution of the magnetic flux density, leading to the emergence of higher harmonic magnetic fields that rotate at different frequencies. Due to the asymmetry of the windings, any higher harmonic of the magnetomotive force (MMF) can exhibit both forward F_{vfr} and reverse F_{vrev} waveforms [8].

Works [1, 9] note that interturn short circuits in the stator winding lead to the emergence of harmonic components determined by the equation:

$$f_{st} = f_1\left(\frac{n}{p}(1-s) \pm \nu\right), \tag{6}$$

where n = 1, 2, 3 – whole numbers;

$\nu = 6 \cdot c \pm 1$ – higher MMF harmonics of the stator winding.

The expression (6) is dependent on slip, meaning that in certain cases, the analysis of the amplitude of harmonic components f_{st} in the current spectrum may be ambiguous.

Typically, when the number of turns in a phase winding decreases, the current increases not only in the damaged phase but also in the other two phases, as the main inductance and active resistance decrease. Works [9, 10] note that when the current in the closed circuit of the damaged phase rises, the third harmonic component of the current significantly decreases, while it increases in the undamaged phases. The emergence of interturn short circuits disrupts the third harmonic MFD in the phase windings. In these cases, the MMF of the third harmonics in the three stator phases forms an asymmetric system, and their sum does not equal zero.

The resultant magnetic field of the asymmetric stator winding is non-circular and pulsates with the frequency of the flux. As the degree of asymmetry in the stator winding increases, the additional harmonics of the MMF also increase.

The slip for higher harmonics can be defined as follows:

$$s_\nu = 1 - \nu \cdot (1-s). \tag{7}$$

And the magnetic flux of the ν-th order harmonics of the stator rotates with the frequency:

$$n_\nu = \frac{n_1}{\nu}. \tag{8}$$

It follows that in a symmetrical three-phase stator winding, higher harmonics of the order ν=6c±1 arise. In the case of an asymmetric stator winding, in addition to the odd harmonics of the orders defined by ν=6c±1, even and fractional order harmonics also emerge due to faults.

Moreover, winding asymmetry does not always lead to an increase in the amplitude of all odd harmonics [9], which is attributed to the instantaneous changes in inductance depending on the rotor's position relative to the stator. Considering this, for diagnosing interturn short circuits, it is proposed to primarily rely on changes in the amplitude of the even harmonics of the asynchronous motor.

It is also worth noting that the increase in the amplitudes of even harmonics may be caused by other faults (such as eccentricity or rotor bar breakage). However, the main indicator of stator winding asymmetry is the fundamental harmonic f_1 and the subsequent modulation of even harmonics at frequencies $2f_1 \div 10f_1$.

In a symmetrical stator winding, the currents in the windings are sinusoidal, resulting in the absence of a constant component. However, with stator winding asymmetry caused by interturn short circuits, the shape of the currents deviates from sinusoidal. Even harmonics emerge due to the appearance of a constant component in the phase currents.

Given that the main indicator of stator winding faults in induction motors is the modulation of the current at the power supply frequency f_1, the spectrum is analyzed based on the output current oscilloscope waveform when diagnosing interturn short circuits. It is advisable to consider the current spectrum in a logarithmic scale of dB/Hz due to the dominant current component at the power supply frequency f_1.

5. Conclusions

1. The influence of interturn short circuits in the stator windings of induction motors on the shape of their stator currents has been theoretically proven. It has been shown that this diagnostic method has a sufficient degree of expressiveness, allowing for a high probability of distinguishing this type of defect from other types of damage in induction electric machines.

2. The rationale for using the amplitude of the fundamental harmonic f_1, for diagnosing this type of defect, along with the subsequent modulation of even harmonics at frequencies $2f_1 \div 10f_1$ has been established. It is proposed to consider the current spectrum in a logarithmic scale of dB/Hz due to the presence of a dominant current component at the power supply frequency f_1.

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ОСОБЛИВОСТІ ВПЛИВУ КОРОТКОГО ЗАМИКАННЯ СТАТОРНОЇ ОБМОТКИ АСИНХРОННОГО ДВИГУНА НА СПЕКТРАЛЬНИЙ СКЛАД ЙОГО СТАТОРНОГО СТРУМУ

В останні десятиліття спостерігається стійка тенденція зростання ролі автоматизованих електроприводів на базі асинхронних двигунів. Це зумовлено об'єктивними факторами, такими як розробка високоточних математичних моделей асинхронних двигунів, що підвищило точність і *функціональність їх систем управління, а також розвиток силових напівпровідникових технологій, що підвищило ефективність і знизило вартість перетворювачів частоти. Тож зазначені факти науково-технічного прогресу спровокували як розширення сфери застосування асинхронних двигунів у керованих електроприводах з важкими умовами пуску, що традиційно реалізовувалися на основі двигунів постійного струму, так і збільшення кількості електроприводів з електричним типом керування.*

Водночас сучасний технічний прогрес призвів і до зростання складності, вартості та технологічності промислового обладнання, що підвищує потенційні ризики аварійних відмов. Ще однією тенденцією, спільною для України та багатьох індустріально розвинутих країн, є збільшення кількості електрообладнання, яке вичерпало свій номінальний термін служби. Оскільки між надійністю та часом напрацювання обертових електричних машин існує обернено пропорційна залежність, це логічно призводить до зростання потреби в ефективних системах діагностики.

У статті теоретично доведено вплив міжвиткового короткого замикання обмоток статорного кола асинхронного двигуна на форму його статорних струмів. Показано, що зазначений спосіб діагностування має достатній ступінь вираженості, що дозволяє з високою імовірність виділити зазначений вид дефекту з поміж інших типів пошкоджень асинхронної електричної машини. Обґрунтованого доцільність використання для діагностування зазначеного виду дефекту амплітуд основної гармоніки f_1, і наступної модуляція парних гармонік на частотах $2f_1 \div 10f_1$. Запропоновано розглядати струмовий спектр в логарифмічному масштабі дБ/Гц внаслідок присутності домінуючої складової струму на частоті мережі живлення f_1.

Ключові слова: *асинхронний двигун, діагностування, коротке замикання, обмотка статора, несиметрія, гармоніка.*

Ф. 8. Рис. 1. Літ. 10.

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