Procedures for Testing and Maintenance of Electric Motors for the Purpose of Determining the Correctness and Reliability at Operating Conditions

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Abstract. Electric motors today are represented in all branches of industry and their supervision is a very complex task to research. Improper maintenance and proper checking of electric motors can cause great damage to the drive. In order to determine the condition of electric motors, it is necessary to perform diagnostics of basic parameters in order to determine the reliability and thus the service life of the motor. This is why fault diagnosis is important for the maintenance of electrical machines. The assessment of the condition of the correctness and reliability of the electrical machine is carried out by the method of measuring the basic parameters. The measured data is compared with the nominal data of the correct motor provided by the manufacturer. Diagnostic measurements are performed on the measurement of winding operating resistance, winding impedance, temperature, current, voltage, power, torque, speed of noise and vibration. The measurement is performed for all three operating conditions: no load, nominal and maximum load. Spectral analysis of these quantities gives a picture of the electromechanical state of the motor. For example, the mechanical state of a motor can be determined from the frequency spectrum of noise and vibration, and the condition of each mechanical part can be estimated on the basis of individual harmonics. The analysis of the measured data provides an assessment of reliability and suggests the method and time of servicing. By applying the appropriate sensors and placing them in the right places, the required sizes can be measured quickly and efficiently, and thus the condition of the motor can be assessed. Non-contact measurement of parameters such as temperature, noise, vibration, current, voltage, speed creates a basis for the development of an automated measuring system, which significantly speeds up and facilitates the assessment of reliability and correctness, especially when it comes to a large number of motors. Proper and periodic measurement as well as proper maintenance can extend motor life and result in increased productivity and financial savings. This paper presents the procedures for measuring the required quantities and making an assessment of reliability and correctness on the same type of motor with a different number of operating hours.

Keywords: Reliability · Maintenance · Spectrum · Processing

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1 Introduction

Three-phase asynchronous motors today surpass all other types of electric motors in terms of the number of installed units. Thanks to the intensive development and application of frequency converters, the asynchronous machine, even in terms of control characteristics, has approached DC machines, and it can be used in very demanding drives. Unexpected failure and failure of a machine from operation can cause high material costs and process downtime of various kinds. By applying adequate diagnostic methods, failures can be detected in time, ie at an early stage of their occurrence. In that case, we make engine changes at the most technologically convenient moment, and the planning of overhaul and purchase of spare parts is facilitated. All this information is useful for both the user and the equipment manufacturer. Recently, modern diagnostic methods are being introduced in the production lines of machines, as an additional segment of the final control. Diagnostics of electrical machines is an area that is developing very intensively in world technical practice. Various methods are mentioned in the literature by which it is possible to establish a whole range of failures of electrical machines. Many external indicators, such as oscillation of ammeter hands, oscillations of rotational speed or increased vibrations, can indicate irregularities in the operation of electrical machines. For reliable fault diagnosis, it is necessary to develop accurate signal processing and observation algorithms, so that the cause can be determined from the obtained data. Therefore, it is very important to know the behavior of the correct machine in operation. Their stator winding is always derived as three-phase whether its phases are connected in a triangle or in a star. The design of the rotor winding depends on the size of the machine and the method of starting. Previously, large asynchronous machines were operated with sliding rings. In these machines, the rotor winding is three-phase, as in the stator, the winding is insulated to ground, and its terminals are connected to sliding coils [1]. This rotor design was used in motors driven by resistor actuators. Testing of electrical machines, including asynchronous ones, is carried out primarily to determine its mechanical and electrical characteristics, but also to check the compliance of the manufactured asynchronous motor with the design data. Tests can be divided into three categories: serial, type and special tests. Batch tests are a set of tests aimed at confirming key features on the machine and detecting any gross manufacturing errors. They are carried out on each machine produced in a particular series. The scope of serial testing is determined by the manufacturer, depending on production experience and market expectations. Type tests are performed on only one machine of a certain series. They determine all the features of the asynchronous machine that are determined by the design documentation. The last group of tests consists of special tests, which are carried out at the customer's request, regardless of the series and type tests. Their content and eligibility criteria are defined by a contract or special rules (e.g. for shipping, transport, explosion-proof installations, etc.). Here, the customer also defines the standards according to which the test in question should be carried out [2]. The most common case where such tests are applied are insulation systems of high voltage machines, special requirements when measuring machine noise, explosion tests, etc. For all tests it is necessary to have predefined acceptance criteria to make it clear whether the test result is acceptable or not. Eligibility criteria are determined by the design documentation or relevant international or recognized national standards. Figure 1 shows a system for measuring and diagnosing failures on induction motor bearings.

Fig. 1. Experimental measuring system for determining faults in induction motor bearings.

2 Measurement of Ohmic Resistance of Stator and Rotor Windings

The stator windings, in the case of pulley motors and rotors, are three-phase alternating windings. In most companies, the calculated values for the accepted ohmic resistances are calculated values, which define the allowable lower and upper limit of the deviation of the measured resistance as a percentage of the ohmic resistance from the calculated data. In the calculation data, the machine designer gives the ohmic resistances per phase, calculated at 20 ºC, regardless of whether the winding is connected in a triangle or a star [2]. Due to the performance of the motor, as well as the specificity of the conditions and the required operating speed in the test station, it is sometimes not possible to measure the ohmic resistance per phase. This mainly applies to motors whose stator (or rotor) winding is connected in a triangle, and the motor is for example made in a closed version. The tester has only winding leads available and is able to measure only the ohmic resistance between the winding terminals. Such an approach to measuring the ohmic resistance also facilitates the calculation of losses in the motor winding because a unique formula is used for all winding designs:

$$P_{Cu} = 1.5 \cdot I^2 \cdot R \tag{1}$$

Where P_{Cu} are the losses in the winding, I is the current flowing through the winding, and R is the ohmic resistance of the winding measured between the terminals. This resistance is measured on all three pairs of terminals U1-V1, U1-W1 and V1-W1.

Calculate the measured resistance between the terminals to the phase resistance, which is done for the winding connected in a triangle according to the expression:

$$R_f = \frac{3}{2} \cdot R \tag{2}$$

and for a winding connected to a star according to the expression:

$$R_f = \frac{1}{2} \cdot R \tag{3}$$

where R_f is the mean value of the phase and R is the mean value of the resistance measured between the terminals. The mean phase resistance can now be converted to a temperature of 20 °C. The value thus calculated is compared with the calculated data. It is very important to measure the winding temperature as accurately as possible during the measurement. The most accurate value is given by built-in thermometers, if the engine has them. If, on the other hand, the engine does not have a built-in thermal probe, the temperature of the housing or terminal is measured.

3 Measurement of Insulation Resistance of Stator and Rotor Windings

Insulation is one of the most sensitive parts of an electrical machine and, especially in the past, failures due to damage and deterioration of insulation were very common. Modern insulation methods, as well as the latest insulation materials, have improved the mechanical and insulating properties. Measuring the insulation resistance is in some ways similar to measuring the ohmic resistance, only in this case the insulation resistance is measured, not the conductor. One end of the DC voltage source is connected to the terminal of the phase to which the insulation resistance is measured, while the other end is connected to ground. In practice, the DC voltage connected to high-voltage motors is 1000 V. While the voltage is connected, the current flowing through the insulation is measured. Insulation consists mainly of insulators with a specific conductivity of less than 10^{-6} S/m. The device that measures the insulation resistance is called a megohm-meter or inductor. It has a custom scale for reading the insulation resistance which, due to the height of the applied voltage and very low current, is measured in megaomes. As the current through the insulator changes its character depending on the start of the measurement, the insulation resistance is read at precisely defined moments. U.S. IEEE regulations define the insulation resistance reading after the first and tenth minutes from onset measurements. European regulations, based on, define that the insulation resistance is read after 15 and 60 s from the start of the measurement. However, failures of large machines caused solely by aging insulation are relatively rare. Much more frequent failures are caused by the penetration of foreign materials (oils, metals…) into the insulation. Damage to the insulation of the phase leads from the machine, which is caused by vibrations, sometimes occurs during operation. For these reasons, it is necessary to include isolation tests in regular diagnostic tests [3]. The basic methods of testing the state of insulation are: low dc voltage test (insulation resistance and polarization factor measurement), high dc voltage test, leakage current measurement, dielectric loss factor (tgδ) measurement, capacity measurement, partial discharge measurement and high voltage dielectric strength test, pulse test. Except for the housing and package, all machine parts and windings that are not connected to high voltage must be earthed. If it is a final test, it needs to be conducted after a warm-up attempt, which is the worst possible case for the engine insulation system. If the winding "withstands" the test voltage for all 60 s without a ground fault, it is considered correct. The final high voltage test is the last test performed on the machine. After all the characteristics are recorded, and all sizes are measured, there are only 60 s left, which the motor separates from delivery or reassembly and re-insulation of the windings. To avoid unpleasant surprises, it is necessary to check the correctness of the windings at all stages.

3.1 Rotor Winding Failures

Rotor cage failures occur especially with larger machines. The most common reasons are the high temperatures that develop in the cage and the high forces to which the rotor is exposed, especially during take-off. The causes of failure in cast rotors can be in the poor construction of the cage, while in rotors with welded rings there are sometimes poor joints between the rod and the ring [14]. In these cases, the fault site heats up more, which further weakens it, and eventually cracks. The places of the most common cracking are precisely the joints of the ring and the rods, as well as the parts of the rods outside the rotor package that are free. Similar failures can also occur as a result of small cage displacements within the package, which occur due to alternating heating and cooling of the rotor. In cases of intermittent operation, when the machine is exposed to large changes in speed or frequent starts, there is a risk of failure due to material fatigue. Early indicators of these failures are pulsations in rotational speed, stator current, and machine leakage currents. An example of a total rotor cage failure of a high voltage motor is shown in Fig. 2.

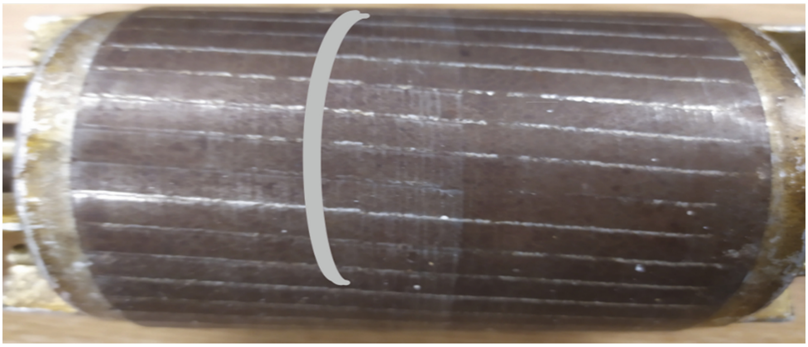

Fig. 2. Example of rotor cage failure

4 Temperature Measurement

Temperature measurement is a common method of monitoring the condition of electrical machines and drives from overheating [4]. Continuous temperature measurement can prevent damage to stator windings and packages, rotor windings and packages, as well as bearing damage (usually combined with vibration measurement). To measure the temperature continuously or intermittently, sensors are used in the design: thermistor, thermocouple, resistant thermometers.

Thermocouples - the work is based on the fact that when two different metals are joined at one end, and the joint is at a different temperature from the free ends, a voltage is induced at the ends of those two metals. The amount of induced voltage is proportional to the difference between these two temperatures. When measuring, it is important that the measured temperature safely reaches the joint of both wires, and therefore they are very often installed on the plates that are inserted into the machine in, for example, ventilation channels. Thermocouples measure temperatures from −250 °C to 3000 °C, depending on the materials used. The most commonly used:

– copper/constant −250 to 400 °C
– iron/constant −200 to 850 °C
– chromel/alumel −200 to 1100 °C
– platinum/platinum rhodium 0 to 1400 °C

Resistance thermometers - elements that determine the temperature from a change in resistance. They have a positive temperature coefficient of resistance and good stability [13]. These are specially made wire resistors that are installed in a characteristic place in the machine with the purpose that the temperature can be measured at that place. Alloys with a high temperature coefficient are used for production, e.g. platinum, nickel. This is most often a Pt 100, a resistor that has a resistance of 100 Ω at 0 °C. It is very important that the measuring current be small because otherwise the meter develops excessive Joule losses, which heat it up and distort the measurement results. Resistance thermometers are better than thermocouples for diagnostic purposes due to the small voltage values induced on the thermocouple. This voltage for the measuring devices needs to be increased which, sometimes, introduces an inaccuracy.

4.1 Bearing Temperature Measurement

The bearing temperature is measured at idle. This test determines the correct installation of the bearing and its lubrication. The test lasts until the bearing temperature stagnates. With larger engines, this can take up to three hours, while with secondary examination almost after an hour and a half. In practice, there are cases that the bearing temperature will not stagnate. This happens when the bearing is not mounted correctly, when it is pinched. The bearing temperature is measured using built-in resistance thermometers. If they are not present, thermocouples (e.g. copper-constant thermocouple) are placed in tubes used to supply grease for bearing lubrication. In this way, the temperature of the outer ring of the bearing is measured.

4.2 Thermal Imaging Diagnostics

The method is based on recording parts of the drive with special thermal imaging cameras. The thermal imaging camera records in the infrared range, and displays the temperatures of the recorded surfaces in different colors. Older versions with liquid nitrogen cooled are bulky, so they are recordings limited to external installations. Newer digital versions work at room temperature, are small in size, and allow recording inside the machine housing. In diagnostic terms, the method can be assessed as moderately effective due to its limitation to visible parts. Gives good results in detecting overheating at junctions, fuses, busbars, conductive insulators (poor contact) and housings (overheating due to stray currents, magnetic flux concentration or specific problems related to high current leads). Measurements are best performed in poor visibility (night or day with cloudy weather). During the measurement, the tested parts of the system should be loaded with at least 50% of the rated currents, in order to reduce possible errors due to the conversion of currents to rated loads.

5 Noise and Vibration Measurement

The noise of electric machines of asynchronous motors is divided into three types. These are aerodynamic noise, mechanical noise and magnetic noise. Aerodynamic noise is caused by the flow of coolant as a result of engine ventilation. Mechanical noise is caused by the rotation of the rotating parts of the engine (bearings, sliding wheels). The last type of noise is caused by magnetic conditions in the machine, which is why it is called magnetic noise [3]. Aerodynamic and mechanical noise are present at and below the supply voltage, while the saturation of the magnetic circuit has not yet occurred. Many failures of electrical machines are accompanied by an increase in vibration of the machine or its individual parts. In the case of many irregularities, vibrations can be reliable indicators of the same. Vibration measurements can detect failures of rotor bearings, rotor cages and a number of other failures. Due to the fact that most failures are also manifested through an increase in vibration, the experience of the person or the quality of the expert system is important for interpreting the results of vibration measurements and making judgments about the possible cause. Nowadays, vibration measurement is one of the most important diagnostic methods in plants. The most common causes of increased vibration of rotary electrical machines are:

- imbalance of the rotor,
- bearing damage,
- incorrect installation and foundation,
- damage to the foundation,
- local resonance of structural parts,
- accidental touching of rotating and stationary parts
- electrical and magnetic asymmetries.

Vibrations can be felt well by touch. Three basic quantities are measured:

vibration amplitude (from 0 to 10 kHz), vibration speed (10 Hz to 10 kHz) and vibration acceleration (1 kHz to >100 kHz).

The choice of size for measurement and analysis depends on the machine being tested as well as the frequencies of interest for the tests. Vibration measurements are performed with vibrometers, proximeters (induced voltage depends on the distance of the object from the sensor), accelerometers (piezoelectric sensors, acceleration measures but are also used to measure speed and displacement; the desired value is obtained by integration). Permissible vibration amounts are determined by regulations.

6 Current Measurement

For current purposes, the drive current signals must be adapted to the measuring devices. Current transformers and shunts are used for this purpose. Shunts are not suitable for measuring large currents as large currents on shunts develop large losses which can create difficulties in shunt construction. In addition, they give relatively small signals. In high-voltage devices, current transformers are also used to isolate measuring equipment from high voltages [7]. Current measuring transformers, as well as voltage ones, are required to have a constant transmission ratio and a small phase shift. For control measurements, as well as in cases when it is not possible to use built-in transformers, current clamps are used. Current clamps are a special design of current measuring transformers that enable connection without the need for prior interruption of the circuit. They are built so that the iron core can be disassembled and covered by a current-carrying conductor. This conductor represents the primary winding of the current transformer, while the secondary is wrapped around the core itself. It is possible to quickly perform a series of measurements with current clamps, as they are easily switched from one conductor to another. This makes them very suitable for diagnostic measurements in operating conditions. “DC transformers” based on the Hall probe principle are used to measure DC and low frequency currents.

7 Shaft Voltage Measurement

Irregularities in the magnetic circuit of an electric machine can cause the existence of a small resultant current in the shaft, which will induce an electromotive force between its ends. This electromotive force is called the shaft voltage, which, if large enough, can cause current to flow through the motor bearings. According to tests conducted in [10], voltages whose effective value exceeds 300 mV can cause current to flow through the motor bearings. This current is dangerous because it causes electrocorrosion on the bearings, which destroys the bearings, ie reduces their service life. In order to avoid the flow of bearing currents, the insulation of one, if not both bearings, according to the mass is carried out. This procedure terminates bearing current circuit. Shaft voltage occurs on all major AC electric rotary machines, and in asynchronous motors the most common causes are:

– the resulting comprehensive flows around the shaft
– higher harmonics of the spatial distribution of flow
– stray currents of foreign sources.

There are two ways to measure shaft voltage. The first measures the voltage drop at the ends of the shaft, so that the stator yoke is included. In the second case, the shaft voltage is measured between the grounded housing and the end of the shaft on which the bearing is insulated. If no bearing currents flow, the shaft voltages measured in both ways do not differ. If, on the other hand, the bearing currents flow, a significantly higher value of the shaft voltage would be measured in the first way than in the second case. Namely, in the first case the induced shaft voltage is reduced only by the voltage drop in the shaft, while in the second case it is also reduced by the voltage drops in the bearing, base plate and motor housing.

8 Data Processing

Data collection is the recording of measured data, the conditions in which the recording was performed (machine load, temperatures, voltages, etc.). The method of data recording is primarily determined by further data processing, ie operations that will be performed recorded data to execute. The data collected must be accurate, of good quality and with as little noise and interference as possible. Many diagnostic systems record data over a long period of time. This method of recording enables quality monitoring of the condition of the machine as well as the development of possible failures and malfunctions. In this case, it is very important that the data is recorded systematically and permanently. In some plants, the tested object is physically distant from the place where data processing and diagnostics are performed, and when recording the size, one should keep in mind the way the data will be transmitted (current signals, optics…), and sometimes on the spot. perform partial processing. In order to be able to diagnose the condition of the machine on the basis of the collected data, it is often necessary to perform a series of operations on the collected data. This is precisely the part in which computers are used the most and for the longest time, and in which a high level of process automation is possible. Data processing can be performed during operation (online) or after the data is recorded and stored (off-line). The most widespread are data processing methods, for diagnostic purposes spectral analysis, correlation and time averaging. The development of measurement and computer technology has enabled the wider application of these methods. Spectral analysis - is the basis of the method of converting signals recorded in the time domain to the frequency domain. By analyzing the signals in the frequency domain (currents, vibrations…) it is possible to detect various faults. Switching to a frequency domain is a display of the frequency spectrum of the recorded signal and the corresponding amplitudes. The basis of the method is the Fourier transform [5]. The idea of the transformation is to show the periodic signal of period T, given by the expression, with uniformly spaced frequency components, which are obtained as:

$$G(f_k) = \frac{1}{T}\int_{-T/2}^{T/2} g(t) \cdot e^{-j2\pi f_k k^t}\, dt \qquad (4)$$

where k represents the k-th harmonic of the fundamental frequency f. Conversely, from the frequency spectrum the time function is obtained according to the expression:

$$g(t) = \sum_{k=-\infty}^{\infty} G(f_k) \cdot e^{j2\pi f_k t} \tag{5}$$

In order to obtain a satisfactory sampling frequency transformation accuracy with FFT, it must meet the Nyquist criterion, which means that the recording must be performed with at least twice the frequency of the highest frequency we want to analyze. In stator current analysis, side harmonics occur at a relatively small distance from the fundamental frequency. Therefore, the Fourier transform needs to be performed at a sufficiently high resolution. In order to increase the transformation resolution N times, it is necessary to collect N times more samples, since it is the number of samples that determines the transformation resolution. Classic FFT gives a spectrum covering frequencies from 0 Hz to the maximum recorded frequency fmax. Higher resolution can be obtained in several ways. The first way is to increase the degree of transformation thus increasing the time required to carry out the transformation. Another possibility is to reduce the maximum frequency. This solution is not always advantageous since it loses more frequencies needed to determine the state of eccentricity. The next solution is to increase the recording time, which automatically gives a better resolution, provided that the consistency of the measured size is ensured throughout the recording.

9 Testing of an Induction Motor for Various Faults of the Rotor Winding by Spectral Analysis of the Stator Current

The circuit diagram used to record the stator current is shown in Fig. 4. The AM asynchronous motor is connected trough a shaft to a DC motor with independent excitation which serves as a load on the induction motor. The magnitude of the load is determined by the regulation of the direct current of the independent excitation, in this case it is 5 A. The stator current AM is measured using current measuring transformers CMT and current clamps CP trough an AD card connected to a computer where the measurement signals are processed (Fig. 3).

Appearance of the current spectrum, at three different states at a load of 5 A: for a machine in good condition, Fig. 4, a machine with one damaged rod, Fig. 5 and a machine with two damaged bars, Fig. 6.

In normal operation, the stator current is sinusoidal and contains only the fundamental harmonic and noise harmonics.

In case there is one damaged rod on the rotor, the fundamental harmonics and harmonics at 75 Hz, 120 Hz and 250 Hz appear in the stator current.

In case there are two damaged rods on the rotor, in the stator current we have the same harmonics at 75 Hz, 120 Hz and 250 Hz but a larger amount.

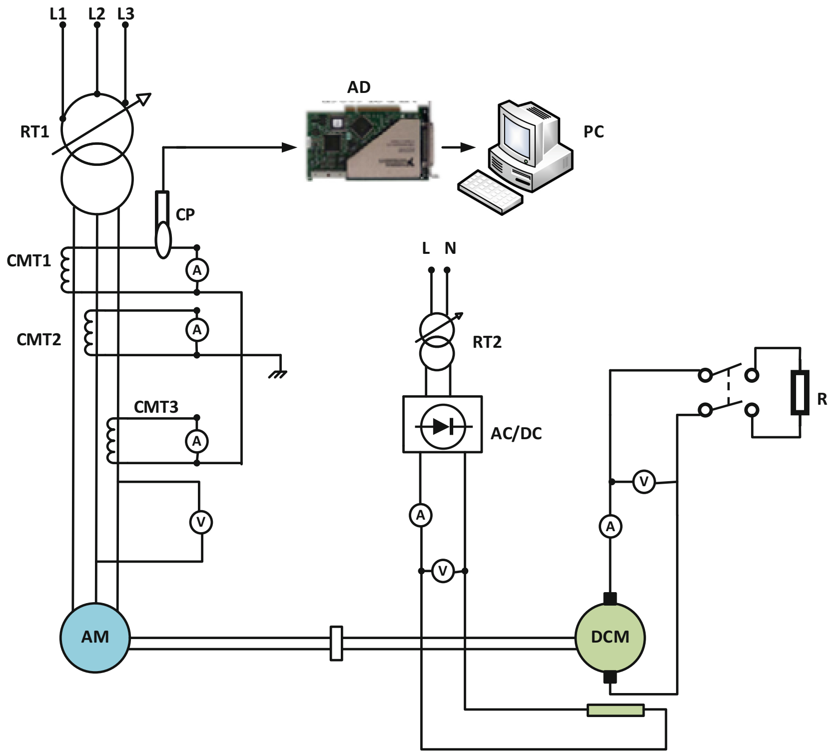

Fig. 3. Laboratory system for recording the stator current spectrum of an induction motor

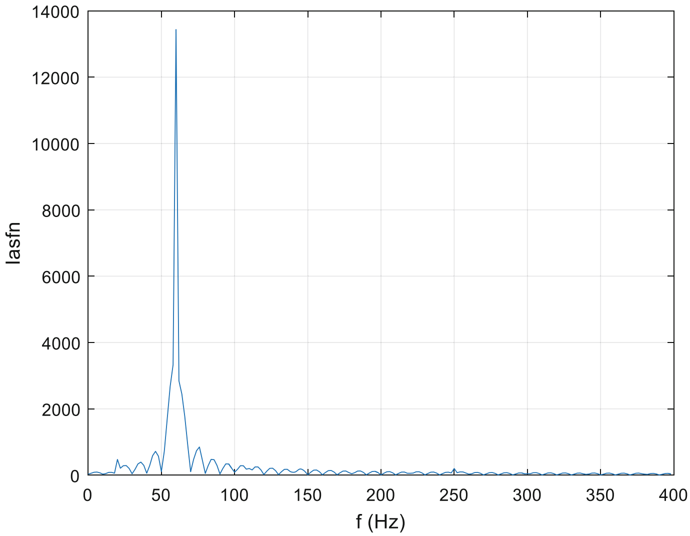

Fig. 4. Appearance of the current spectrum at a load of 5 A for the machine in normal operation when working on the network

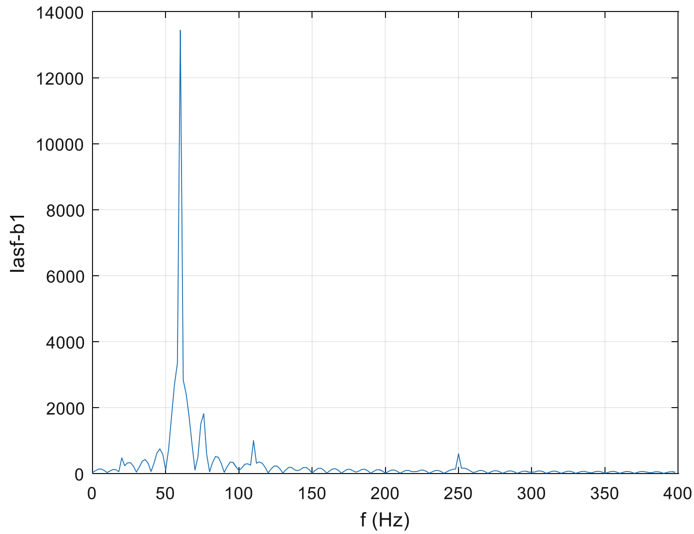

Fig. 5. Appearance of the current spectrum at a load of 5 A for a machine with one cut rods when working on the network

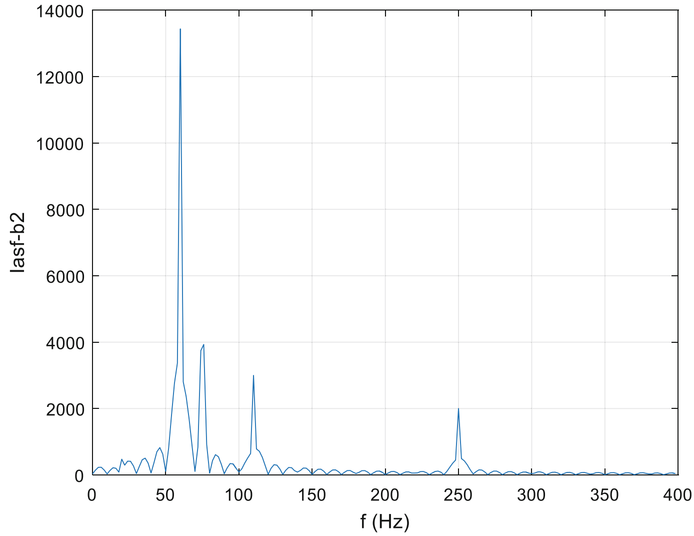

Fig. 6. Appearance of the current spectrum at a load of 5 A for a machine with two cut rods when working on the network

10 Conclusion

Diagnosis is the timely or periodic determination of the condition of a machine in order to assess the reliability of further operation and suggest ways and scope of servicing [6]. The role of diagnostics is to detect malfunctions of the machine or its individual parts at the earliest possible stage. Monitoring the condition of the machines facilitates the planning of maintenance and repairs, thus reducing the downtime due to the replacement and repair of machines to a minimum. In cases where quality mon toring is carried out, many unnecessary plant shutdowns are avoided. The basis of diagnostics is a comparison of actual and desired behaviors or machine parameters. In addition to theoretical knowledge, it is very useful and experiential knowledge of the behavior of the machine in certain fault modes. Quality monitoring and diagnostics requires the observation and processing of a range of electrical quantities. Many of these tasks today are solved using computers. The process of fault diagnosis is very demanding since different faults can be equally manifested, ie reflected on the operation of the drive. The diagnosed fault is assessed and based on the assessment, a decision is made to continue or stop the operation of the plant. In cases when the deviation is small and when there is no danger of major damage, the plant continues to operate, and the data obtained are used to plan repairs and purchase spare parts. In case of larger deviations, overhaul is planned as soon as possible. In the event of very large deviations, ie faults that are dangerous for further operation, the drive is stopped and the fault is rectified. The method of spectral analysis of stator current proved to be one of the most interesting methods. This method is applicable to asynchronous machines of a wide range of powers and applications. In addition, it does not require the installation of additional measuring members, nor the shutdown of the drive. For these reasons, much of the work is devoted to this method. The method is based on the fact that each occurrence of asymmetry (damage) of the rotor cage, in the spectrum of the stator current causes the appearance of side harmonics, distant from the mains frequency by the amount of 12sf±. The condition of the motor cages can be determined from the values of the side harmonics. From the recording it can be concluded that the values of the side harmonics change significantly with the load of the machine. For these reasons, it is important to record at the highest possible load on the machine. The changes in the values of the harmonics are shown in the table and graphically. The power supply from the frequency converter reduces the values of the side harmonics in relation to the values when working on a rigid network for the same load. Such values may lead to the conclusion that the machine is in better condition than the actual one. In addition, changes in harmonics, by changing the load are less pronounced.

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