Capabilities for diagnostics of pump system's electrical equipment via frequency converters

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***Abstract* — The paper examines the possibilities of performing diagnostic tests on the induction motors using frequency converters. The methods and algorithms for the implementation of the diagnostic functions of frequency converters are presented. Some practical cases from the exploitation of frequency converters in pump systems are shown to demonstrate their diagnostic capabilities.**

***Keywords* — diagnostic capabilities, diagnostic techniques, fault detection, frequency converter**

I. INTRODUCTION

In the current stage of development of technics and technologies the requirements for electric drives are constantly increasing, in order to increase the quantity and quality of the produced products and reduce their cost. In the presence of problems such as aging, high requirements for reliability, and price competitiveness, the diagnostics of electrical machines and electric drives is becoming increasingly important. Another major issue in the field of diagnostics of electrical machines, which is still one of the main problems under research, is the possibility of developing diagnostic techniques that could use generalized diagnostic parameters even in non-stationary operating conditions.

Nowadays frequency converters are a standard element of many automated production units, as they offer the ability to smoothly adjust the speed of the motors and give the drive great flexibility and high energy performance. However, their increased implementation leads to some difficulties in the diagnosis of electrical and mechanical failures in the electrical drives, since the variables that are commonly used for technical diagnostics are inevitably affected by the way of controlling the motor. Therefore, methodologies and techniques for diagnosing and condition monitoring of motors powered directly from the mains can hardly be implemented in adjustable asynchronous electric motors. This disadvantage is offset by the presence of a microprocessor system that allows the use of advanced algorithms for signal processing and analysis of the results obtained in order to determine the technical state of the drive elements. Methods that are implemented for fault identification include several different areas of science and technology. They can be classified as:

- Electromagnetic field monitoring;
- Temperature measurement at specific points of the machine;
- Monitoring of the transmitted radio frequency signals;
- Monitoring of vibrations and acoustic noise;
- Analysis of the spectral signature of the motor current [1].

Frequency converters collect and generate large amounts of information necessary for the purposes of process control. Often this data can be used to diagnose not only the device itself but the entire technology chain. This means that information is available in huge quantities at all the time, allowing the selection of the "best" diagnostic parameters, taking into account both short and long-term system status assessments. The ability to measure, store, and transmit data depends on the frequency converter itself and its control platform. Initially, the signals (parameters) that are measured or calculated are written in a regularly updated table. The instantaneous values of the signals can be read from this data table, in the form of operating parameters and stored in the so-called Data loggers. The data saved in the Data loggers could easily be used for equipment diagnostics [2].

II. CAPABILITIES FOR DETECTING ELECTRICAL FAULTS AND SUPPLY ABNORMALITIES

The electrical faults of the motor are related to the deterioration of the insulation of the machine. This deterioration is due to the fact that during operation the insulation is constantly exposed to a combination of thermal, electrical, and mechanical stresses, and the insulating material gradually degrades. The failure rate of motors powered by frequency converters is higher due to the increased electrical and thermal stresses of the insulation material. Continuous operation at a high rate of change of voltage dV/dt due to pulse width modulation results in short-term overvoltages (up to 3 times the voltage of the intermediate DC-link) and uneven distribution of voltage across the turns of the stator windings. This significantly increases the electrical stress of the main and inter-turn insulation. In addition, the thermal stress of the stator insulation increases due to the reduced cooling capacity at low-speed operation and increased losses [3].

Faults of the stator windings can be divided into two main categories:

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- faults causing significant (full) asymmetry in the electrical parameters of the windings - interruptions of the windings and ground or interphase short circuits;
- faults causing small (partial) asymmetry in the electrical parameters of the windings - inter-turn short circuits.

This classification is based on the mathematical model of the machine, which is very different in the two classes of failures. In the case of full asymmetry of the windings, the usual models of the machine are applied, and the parameters of the damaged winding are changed. While in the presence of inter-turn short circuits, the structure of the equations in the mathematical model changes due to the increase in the number of state variables.

Generally speaking, faults in the electric machines change the symmetry in their parameters. In turn, this leads to fluctuations in the measured signals, having different frequency, magnitude and phase, which depend on the type of fault. The monitoring of the technical condition of the electric drive is achieved by relying on easily measurable electrical or mechanical quantities such as current, voltage, resistance, magnetic flux, torque and angular velocity [4].

Standard insulation tests, including measurement of insulation resistance, capacitance, and dissipation factor (tangent from the angle of dielectric losses), allow the detection of insulation problems caused by moisture absorption, contamination, etc. These tests may be carried out by means of the frequency converter with the motor at standstill, for which purpose the scheme shown in Fig. 1 or its modifications shall be applied.

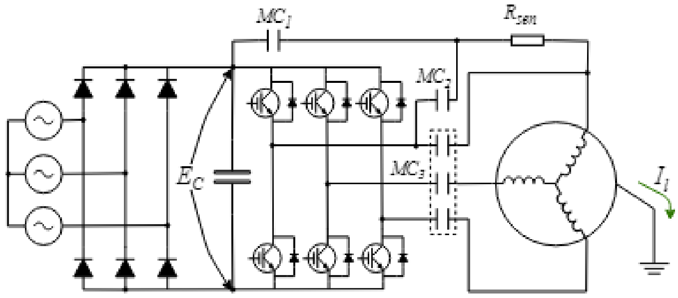

Fig. 1. Scheme for measurement of the insulation resistance via variable frequency drive

When measuring the insulation resistance, contacts MC2 and MC3 are open, while MC1 is closed, applying the rectified voltage from the intermediate DC-link, through the leakage current sensor, to the motor winding. The insulation resistance can be calculated as:

$$R_{ins} = \frac{E_C - \bar{I}_l R_{sen}}{\bar{I}_l}, \qquad (1)$$

where: $\bar{I}_l$ is the DC component of the leakage current;

R_{sen} - internal resistance of the sensor (typically between 0,1 and 1MΩ);

E_C - rms value of voltage in the intermediate DC-link.

Schemes containing mechanical contacts find limited practical application due to the presence of additional elements. In practice, more often the DC voltage from the rectifier is applied to the windings using the elements of the inverter. However, this leads to measurement errors caused by leakage current in the inverter elements. Another issue when using this technique is that the rectified voltage has ripples and the current contains both AC and DC components.

The measurement of the insulation capacity could be done by using voltage with mains frequency or any frequency modulated by the inverter. This voltage is applied to the winding by closing the contact MC2, and opening MC1 , while MC3 remains open. The value of the insulation capacity can be determined by the following dependence:

$$C_{ins} = \frac{\tilde{I}_l \cos\delta}{\omega(V_{ph} - R_{sen}\tilde{I}_l)}, \qquad (2)$$

where: $\tilde{I}_l$ is the value of the leakage current when performing a test with AC voltage;

V_{ph} - rms value of the modulated phase voltage;

ω - angular frequency of the modulated voltage;

δ - angle of dielectric losses.

The determination of the dissipation factor (tangent of the angle of dielectric losses) is performed after measuring the active resistance and the insulation capacity, using the formula:

$$DF = \tan\delta = \tan\left[\arcsin\left(\frac{\bar{I}_l}{\tilde{I}_l}\right)\right]. \qquad (3)$$

Inter-turn short circuits in the windings account for a large part of motor stator windings failures. The simplest and easiest technique for detecting faults in the inter-turn insulation, which has gained the widest application in frequency converters, is the resistance imbalance test (RIT). The resistance imbalance test can be performed automatically, using the inverter, whenever the motor is at a standstill position. Normally, the resistance of the windings is measured each time the motor is started or at a predetermined number of operating cycles. The resistance of the windings is calculated by means of the voltage of the intermediate DC-link and the current values I_{ij} in the individual phases obtained during several periods of pulse width modulation with a duty factor *D*:

$$R_{ij} = \frac{(E_C - 2V_{CE})D + (-V_{CE} - V_D)(1-D)}{2I_{ij}}, \qquad (4)$$

where: V_{CE} is the voltage drop across a turned-on IGBT;

V_D - voltage drop on a turned-on fly-back diode.

Despite its simplicity and obvious advantages, the resistance imbalance test also has its disadvantages:

- constant monitoring of the technical condition is not possible;
- errors in the assessment of the technical condition due to the influence of contact resistances.

In addition to the classical methods for testing and diagnostics of electric machines, modern methods applicable in frequency regulators are considered. They are based on an analysis of the spectral signatures of electrical quantities, as well as methods using injection of high-frequency components of the signal.

As already mentioned, the faults in the stator windings are associated with the appearance of asymmetry of the electrical parameters. This asymmetry causes a negative sequence current I_n, which is used as a diagnostic feature in embedded diagnostic systems. In the event of a fault related to complete asymmetry, the reverse sequence current is equal to the positive sequence current I_p. This makes the faults clearly identifiable and easy to detect. In the case of a fault related to partial asymmetry, the magnitude of the negative sequence current depends on the size of the fault (the number of short-circuited turns). In such cases, detecting faults with a small number of short-circuited turns is complicated.

One well designed and effective diagnostic technique (procedure) should distinguish the negative sequence caused by even a small inter-turn short circuit. This procedure must be related to at least a few basic parameters of the machine, allowing the distinguishment of the negative sequence caused by faults and the negative sequence caused by unbalance of the supply voltage or saturation of the magnetic system.

In order to take into account, the influence of power supply by an unbalanced voltage system, both current and voltage signals should be measured. In this case, the negative sequence impedance can be calculated:

$$\begin{bmatrix} V_p \\ V_n \\ V_z \end{bmatrix} = \begin{bmatrix} Z_{pp} & Z_{pn} & Z_{pz} \\ Z_{np} & Z_{nn} & Z_{nz} \\ Z_{zp} & Z_{zn} & Z_{zz} \end{bmatrix} . \begin{bmatrix} I_p \\ I_n \\ I_z \end{bmatrix}, \qquad (5)$$

where: V_p, V_n, V_z are the voltages of the positive, negative and zero sequences;

Z_{ij} is the *i*-th sequence impedance, caused by the current with *j*-th sequence.

The negative sequence impedance is a parameter with a relatively constant value for fault-free machines and a highly variable value for faulty machines.

Studies in the field of the electrical machine diagnostics show that a negative sequence impedance deviation greater than 6% is usually a clear indication of a stator winding failure.

Another technique for detecting stator faults involves the injection of high-frequency signal components. Injecting high-frequency signals is an effective way to detect spatial asymmetries in AC machines. The use of a low-amplitude, high-frequency, voltage signal superimposed on the main supply voltage provides the following advantages:

- the value of the negative sequence impedance for the high-frequency signal does not depend on the operating conditions of the machine - magnetic flux (scalar Volt/Hz control), load and frequency of the supply voltage and changes only in the event of a fault;
- the influence of the current regulators, which are an integral part of all variable speed electric drives, is significantly reduced;
- the high-frequency signal is injected by means of the frequency converter and uses the possibility to compensate for the changes in the voltage of the DC intermediate unit, which significantly reduces the influence of the supply voltage unbalance [5].

Electric faults in the rotor cover 5 to 10% of the total number of faults in induction motors. Although less common, rotor faults are difficult to diagnose. Unlike stator faults, in which the motor is normally switched off within a few minutes of the fault, rotor faults do not cause the protective equipment to trip. This means that the operating time of the motor in the event of a fault is not limited. On one hand, the current in the rotor bars adjacent to the faulty (interrupted) one can increase by up to 50%, leading to a potential increase in the fault. On the other hand, the interruption of the rotor bars leads to an increase in the stator current, which causes the stator windings to overheat.

The detection of faults in the rotor bars and end rings is performed simultaneously with the detection of faults in the stator and rotor magnetic cores. For this purpose, the frequency converter is used to excite a pulsating magnetic field from the individual windings. The power P_f required to create the pulsating magnetic field for each of the phases is measured. When performing the measurement, the change in the power required to create a magnetic field at different locations (angles) of the field source is obtained. In the case of fault-free magnetic core and rotor bars, the magnetic system is symmetrical and the power required to create a magnetic field will be constant. In the presence of a fault in the magnetic cores or the rotor bars, power fluctuations will be observed. The maximums of these fluctuations are obtained at the location of the fault [6].

Another method used to detect electrical faults in the rotor of induction motors is the motor current signature analysis. It is known from the theory of the rotating magnetic field that any asymmetry in the rotor leads to the appearance of the current component with frequency:

$$f_{rot} = f(1 \pm 2ks), \qquad (6)$$

where: *f* is the motor supply voltage frequency;

$k = 1, 2, 3 \ldots$

s – slip with which the motor operates.

Many different diagnostic approaches can be found in the literature using different combinations of electrical signals. One of these methods is the so-called Vienna monitoring method (VMM), which is applied to detect rotor faults in vector-controlled machines. This technique is based on measuring the voltage and current of the motor and the angular position of the rotor, on the basis of which the deviation of the torque obtained from two different mathematical models of the machine is checked. This procedure is quite common, as it offers a quantitative diagnostic indicator that is independent of the moment of inertia and the load of the electric drive.

III. Capabilities for Detecting Mechanical Faults

The distribution of faults in electric drives shows that over 65% of failures are caused by mechanical damage. Damage to the bearings can be due to wear of the outer or inner bearing ring, wear of the rolling elements and breakage of the separator. Vibrations, mechanical loads, rotor eccentricity and currents flowing through the bearing due to electronic power supplies contribute significantly to the development of these faults.

Bearing faults are usually detected by measuring vibrations. However, the use of electrical signals is preferable in many applications. A number of studies have dealt with the diagnosis of bearing failures based on the motor current signature analysis (MCSA). The physical connection between vibrations and current components can be represented as follows: the vibrations with frequency f_{car} lead to oscillations in torque $M(t)$ and angular velocity $\omega(t)$ of the motor. These oscillations cause fluctuations in the magnetic flux and hence in the current of the machine. These current fluctuations are periodically variable components with different frequencies, depending on the type of fault. Therefore, vibrations are represented as the torque component that generates the components of the current with frequencies:

$$f_{bear} = \left| f \pm k f_{car} \right| . \qquad (7)$$

The frequency of vibration (carrier frequency) f_{car} of the motor shaft associated with damage to the individual elements of the bearings - inner F_I and outer F_O bearing ring, separating cage F_C and rolling elements F_B can be determined by the following dependencies:

$$F_I = \frac{N_B}{2} F_R \left(1 + \frac{D_b \cos\beta}{D_c} \right), \qquad (8)$$

$$F_O = \frac{N_B}{2} F_R \left(1 - \frac{D_b \cos\beta}{D_c} \right), \qquad (9)$$

$$F_C = \frac{1}{2} F_R \left(1 - \frac{D_b \cos\beta}{D_c} \right), \qquad (10)$$

$$F_B = \frac{D_c}{D_b} F_R \left[1 - \left(\frac{D_b \cos\beta}{D_c} \right)^2 \right], \qquad (11)$$

where: F_R is frequency that corresponds to the rotor rpm ;

N_B - number of the bearing rolling elements;

D_b - diameter of the bearing rolling elements;

D_c - pitch diameter of the bearing;

β - contact angle of the rolling elements.

For a given design of the machine and frequency of the supply voltage, the frequencies of the generated current components can be determined. These components usually have a very small amplitude and special digital signal processing techniques are used to detect them. The digital processing techniques that have found the widest application are fast Fourier transform FFT and discrete wavelet transform DWT [7].

IV. Conclusions

Frequency converters provide an effective solution for periodic and automated monitoring of the technical condition of electric motors, providing better reliability and efficient maintenance.

During the diagnostic tests of the motor, information on the technical condition of the elements of the frequency converter is also obtained, which leads to an increase in the reliability indicators for the entire adjustable electric drive.

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