CONTACTLESS DIAGNOSTICS OF INDUCTION MOTORS FOR HYDRAULIC UNITS

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Abstract: *In the case of energy-efficient drives with induction motors, the tendency to implement optimally designed motors, combined with intelligent control, incorporating an integrated monitoring and diagnostics system, is becoming increasingly important. Induction motors in industrial systems operate with frequent starting, dynamic loads and sometimes unbalance of supply voltage. In order to maintain an optimal operating condition, reduce the number of failures and build up an optimal repair and maintenance system, it is important to have an advanced monitoring system coupled with fault identification techniques. The behavior of optimally designed three-phase induction motors designed to operate integrated into hydraulic units with continuous duty operating mode is considered.*

KEYWORDS: *INDUCTION MOTORS, MOTOR DRIVES, CONDITION MONITORING.*

1. Introduction

In general, the physics of operating failures in induction motors (IM) is very complex and many failures can occur almost simultaneously. The mechanism of aging of the insulation and the wear mechanism of the bearings is combined with the simultaneous action of the operating loads. Both work and startup processes are altered. Diagnostics of IM in working mode is preferred because the damages are established at the stage of their origin. One of the main directions for the improvement of modern diagnostic systems (DS) is the most reliable assessment of the technical condition. The behavior of optimally designed three-phase induction motors of a particular manufacturer, the ATM series, designed to operate integrated in hydraulic units in continuous duty mode S1, such as metal cutting machines, injection molding machines and other hydraulic equipment, is considered. Two types of motors are being tested, which are complied with in accordance with EN 60034/2014: ATM 100L-4 and ATM 100L-BH-4.

2. Electrotechnical considerations

To evaluate the functional state of an electric motor, a complex criterion based on observation and analysis of the momentary values of phase currents and voltages in operating mode can be used [1], [2]. A method of symmetrical components of stator currents and angle of inclination of the mechanical characteristic in the field of operating slips is applied. This non-contact method can be automated and used to diagnose turn-to-turn faults (interwoven short circuits) in the stator winding, bearing failure, increased eccentricity, defects in mechanical reinforcement and mechanical parts of the machine.

Similarly, turn-to-turn faults can be detected in the stator winding, bearing failure and increased eccentricity. The degree of failure is determined by signal gradation compared to its magnitude at 50 Hz. Frequencies typical of individual failures very rarely coincide or are close. In addition, the monitoring system and subsequent spectral analysis allows accuracy of up to 0.01 Hz. In the case of repeated measurements, a database is created to track the course of the damage in time, which in turn allows repairs to be planned. Voltage monitoring allows detecting asymmetry, presence of higher harmonics at different rotational frequencies, presence of pulse overvoltages, common in working with power electronic devices. It is known that the first two causes overheating of the stator winding and damage to the bearings due to the occurrence of high-frequency torques with reverse sequence.

In the case of high-frequency harmonics in voltage and phase asymmetry, these methods make errors in the diagnostic evaluation. For database completeness it is recommended to collect both parameters in static (inactive) and dynamic (active) state. The correlations between these test data allow for a realistic assessment of the current working situation and a reliable forecast of its working ability. Systems operating on this principle are the MCETM (Parameter Analyzer) and DMA (Dynamic Analysis System) manufactured by PdMA® Corporation. The MCEGold® software is used to analyze data from measurements and databases, thus tracking the trend of variables over time. The diagnostic system and algorithm is aimed at detecting the most damaging components and machine assemblies. It is possible to conduct an operational analysis of the significance of the defects and to make recommendations for further actions. The work of the system is in line with the criteria imposed by standards of the EPRI (The Electric Power Research Institute, USA) and IEEE (Institute of Electrical and Electronic Engineers). The following parameters are subject to constant control:

- Voltage quality - overvoltage, phase asymmetry, presence of high frequency impulses;
- Complex resistance of windings, inductances;
- Mutual inductance between stator and rotor windings. Thus defects in the rotor winding - breaking the connection of rotor rods and short-linking rings, short circuits between the rods and steel, static and dynamic rotor eccentricity are detected.

Conclusion of the occurrence site (stator or rotor) and the type of failure (interruption of parallel branches from stator winding, interruption or loosening of rotor rods, turn-to-turn faults, disturbed contact between short circuit rings and rotor rods) is given after a detailed analysis of multiple measurements.

Any failure results in electrical or magnetic asymmetry in the machine, therefore the magnitude and frequency of the reverse sequence current provides good information for most common failures: turn-to-turn faults, dropping parallel clones or rotor winding rods, defects in the mechanical part, etc. The accurate and immediate measurement of phase currents and the selection of a suitable algorithm for calculating the symmetrical components of currents or voltages at their instantaneous values ensure the reliability and accuracy of the diagnostics. In addition, the main drawbacks of most DSs associated with the use of multiple sensors are avoided [3].

Comparative analysis of diagnostics approaches have been presented in [4].

3. Measurements and results obtained

In order to assess the functional condition of induction motors as part of a hydraulic installation, dynamic monitoring has been conducted. Non-contact monitoring techniques are selected by real-time analysis of instantaneous values of currents, voltages, and power in operating mode. The tested motors are fed by a powerful grid, their load is changed by a dynamometer, and the operating parameters are monitored using a METREL MI 2292 energy quality analyzer.

The aim is to establish the technical condition and reliability in case of different loads. The observed operating parameters are: currents and voltages in each phase, active and reactive power for each phase, voltage frequency, temperature. Under experimental conditions, different loads are imitated when changing the supply voltage. The technical data and parameters of the equivalent circuit of the investigated induction motors are given in Appendix. These electric motors, the object of development, are new induction motor with squirrel cage rotor, produced by Caproni JSC, Bulgaria.

In fact, in an unsaturated asynchronous machine, there are many spatial harmonics, determined by the non-sinusoidal distribution of the magnetizing forces and the unevenness of the air gap (presence of stator and rotor channels, presence of eccentricity). In the saturated magnetic system of the machine, harmonic spectra also arise due to the non-linearity of inductances and mutual inductances. Only a small part of the harmonics have an impact on the operation of the machine. Most of them have very small amplitudes and can practically be ignored.

By acquiring the three line voltages and currents of the motor in real time total harmonic distortion is calculated in [5].

The measurements for the voltages and currents of the three-phase induction motor type ATM 100L4 are presented in *Fig. 1* and in *Fig. 2* - their harmonics composition.

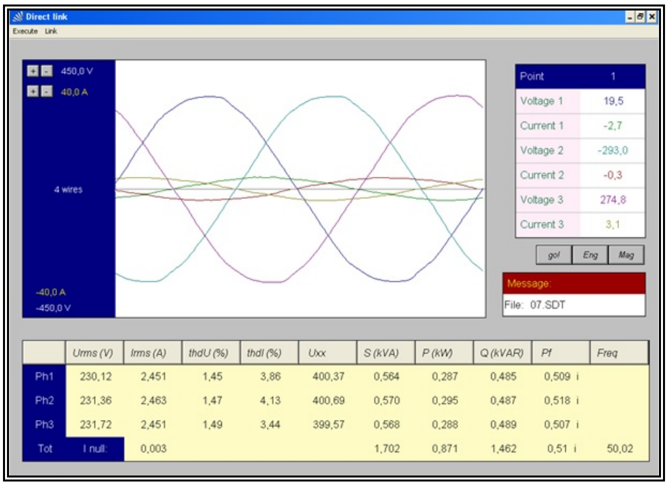

Fig. 1 *Voltages and currents measured of the three-phase induction motor type ATM 100L4*

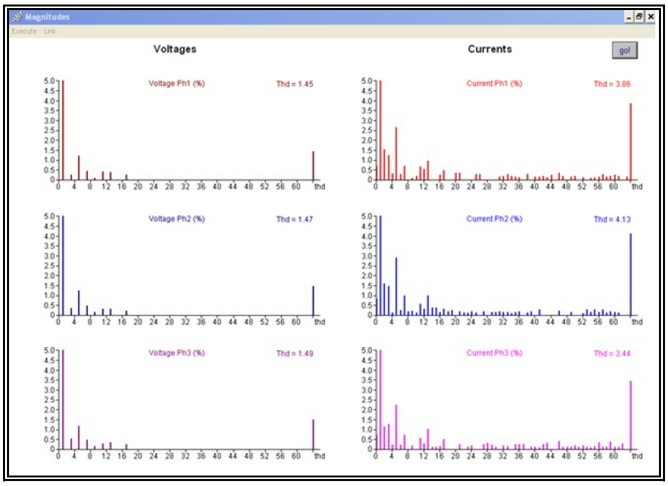

Fig. 2 *Harmonics composition of the voltages and currents measured*

A simple and reliable technique for diagnostics of induction motor current electrical and technical condition uses the ratios between the main and third voltage harmonics [3]. It is known that the stator's magnetization curve is highly non-linear. In the sinusoidal shape of the current, the curve of the magnetic flux is non-sinusoidal due to the non-linearity of the inductances and the mutual inductances. In the composition of the magnetic flux, a third harmonic is the strongest manifestation. When connecting the stator winding to a star, as in the case we are considering, the respective harmonics of electromotive force (e.m.f.) is induced in each phase. Some of the experimental data taken at different supply voltages are presented in Table 1 as the base voltage value is assumed to be the nominal value.

Table 1: *Values of third harmonic according to supply voltage*

		U(3), %		
		Phase A	**Phase B**	**Phase C**
U*	0,90	1,37	1,34	1,37
	0,95	1,35	1,38	1,39
	1,00	1,42	1,48	1,45
	1,04	1,45	1,48	1,47

Determining the magnitude of the third harmonic is the degree of saturation of the steel and the position of the operating point from the magnetization curve, i.e. the value of the magnetic induction. When working under load the position of the working point is changed. When the load is increased, the operating point descends down the B(H) curve, as a consequence of the rise of the falls $I_1 \times r_1$, $I_1 \times x_1$ and the dissipation inductive resistance of the winding, and the degree of saturation of the steel.

Reduces inducted e.m.f. and the corresponding harmonics. When the load is reduced, a phenomenon is observed, contrary to what has been described - increasing the inducted e.m.f. and harmonics. Thus, when changing the operating point, the inducted e.m.f. and its third harmonic are altered simultaneously. The connection between the voltage and its third harmonic is, Fig. 3:

$$U_{(3)} = c \times U^3 \qquad (1)$$

where the coefficient c depends on the winding type, the type of the winding curve, the winding coefficient and the frequency of the voltage.

On the basis of the data obtained, it is possible to trace the degree of saturation of the steel at different loads if necessary.

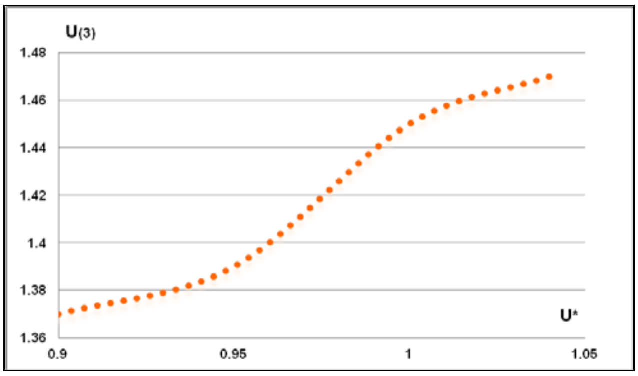

Fig. 3 *Dependence of the percentage of the third harmonic U(3) from the relative value of the voltage U*.*

With some approximation, it's getting

$$\frac{\Delta U_{(3)}}{U_{(3)STEADY}} = 3 \times \frac{\Delta U}{U_{STEADY}}, \qquad (2)$$

where $U_{(3)STEADY}$ and U_{STEADY} are the values in steady-state mode, and $\Delta U_{(3)}$ and ΔU are the variations for deflection from the established operating condition.

Spectral analysis of stator current is another established and popular diagnostic technique. There are basically two approaches [6], [7]: stator current monitoring and its harmonic composition and monitoring of generalized stator current. Stator current spectral analysis is used as a non-contact sensorless technique to determine the rotational speed of the motor under consideration. The arrays with instantaneous current data are used for Fourier harmonic analysis (FFT) and on this basis the amplitude-frequency characteristic of the stator current i_c is built. In *Fig. 4* an oscillogram of stator current and its amplitude-frequency characteristic is presented for the motor under consideration.

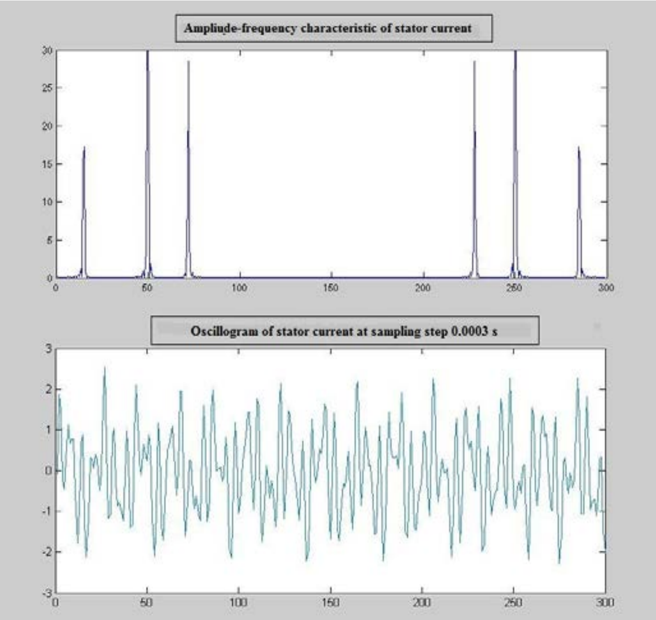

Fig. 4. *Amplitude-frequency characteristic and oscillogram of stator current*

Rotor rotational frequency and slip rates can be determined by the known formulas:

$$s = f_r / f \qquad n = n_1(1-s),$$

where f_r - frequency of the main component of the rotor current, f - frequency of the power supply grid, n - rotor rotational frequency, n_1 - rotational frequency of the stator magnetic field.

Direct measurement of the frequency of the rotor current in a short-circuited rotor winding is impossible. It is therefore convenient to use a non-contact sensorless technique to determine the rotor rotational frequency of the stator current spectral composition. After Fourier transforms (FFTs) for the data array with the instantaneous stator current values, we detect the existence of both the power supply grid frequency *f* and the higher *(f_H)* and lower *(f_L)* components, then we use the established relationships between them to determine the frequency of the rotational frequency only by spectral analysis of stator current.

Relationships are as follows:

$$f_{r1} = f - (f_H - f); \; f_{r2} = f - 2(f - f_L) \quad (3)$$

$$s_1 = 3 - 2\frac{f_H}{f}; \quad s_2 = 2\frac{f_L}{f} - 1 \quad (4)$$

$$n_{r1} = n_1(1-s_1); \quad n_{r2} = n_1(1-s_2) \quad (5)$$

where f_{r1}, s_1, n_{r1} are respectively the rotor current frequency, slip and rotor rotational frequency determined using the frequency of the stator current component f_H;

f_{r2}, s_2, n_{r2} are respectively the rotor current frequency, slip and rotor rotational frequency determined using the frequency of the stator current component f_L.

4. Conclusion

Voltage and current harmonics lead to additional losses in stator and rotor windings and in steel. Additional losses are the most serious effect of harmonic influences and lead to local overheating, most commonly in the rotor. The tolerance levels of the harmonics are determined by what voltage levels and reverse link currents are created. The rotational torques created by the higher harmonics are small and are usually not taken into account but can cause significant shaft vibrations.

Typical of the motors studied is that they are subject to specific requirements for the operating mode and the limited space in which they are placed. A robust and compact automated monitoring system is needed. The non-contact diagnostic techniques offered provide this capability to track motors performance in line with the specific application.

Appendix

INDUCTION MOTOR DATA AND ELECTRIC EQUIVALENT CIRCUIT PARAMETERS

Description	Data	Data
Type, Designation	ATM 100L4	ATM 100LBH4
Rated power (P_{rated})	2.2 kW	3.0 kW
Rated stator voltage (V_{rated})	400 V	400 V
Operating frequency (*f*)	50 Hz	50 Hz
Line stator current (I_1)	4.95 A	6.30 A
Rated torque (T_{rated})	14 Nm	19 Nm
Pole pair number	2	2
Rotor speed (N_r)	1435 rpm	1450 rpm
Power factor	0.80	0.79
Efficiency	80.1%	86.5%
Stator resistance r_1	2.400 Ω	1.680 Ω
Rotor resistance r_2'	2.206 Ω	1.686 Ω
Stator leakage reactance x_1	3.040 Ω	2.564 Ω
Rotor leakage reactance x_2'	3.243 Ω	2.559 Ω
Magnetizing reactance x_m	76.831 Ω	62.287 Ω

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