THE APPLICATION OF THE CONSUMED CURRENT SPECTRAL ANALYSIS FOR THE MONITORING OF BEARING UNITS OF INDUCTION MACHINES

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Abstract. The work suggests a method of diagnostics and monitoring of bearing units in induction electric machines according to the spectrum of the consumed current. The method is based on the assignment of character frequencies generated by the rotating parts of rolling bearings. The faults of the bearing units cause periodic changes in the instant speed of the rotor, short-time changing of rotating electromagnetic torque, redistribution of magnetic field fluxes in air gap and occurrence of highest harmonics in the spectrum of consumed current. Analysing the spectrum and its changes during a particular period of time allows the diagnostics of bearing units faults, monitoring and possible prognosis of bearing units residual life.

Keywords: induction motor, spectral analysis, high harmonic, bearing units, monitoring, air gap.

Introduction

The induction electric motors are widely applied in the industry. They consume up to 70-80 % percent of all the produced energy. The breakdown of an induction motor results in the stoppage, idle time, accidents in the processes. This in its turn results in the increased economic expenses. The induction motors take about 20-25 % of the industrial installation failures. Most of the failures are caused with wrong technical maintenance of the induction motors or even with its full absence. In turn up to 30 % of all possible faults of induction motors fall on the bearing units. Therefore the routine inspection (monitoring) of the technical condition of induction motors bearing units is economically reasonable and effective. It allows before-the-fact prevention of incipient failures and reducing them from the category of sudden failures to those being gradual.

Materials and methods

The traditional methods of vibro-monitoring of bearing units are well-known [1, 2]. Alongside with high effectiveness of this method it also has some disadvantages. For example, in certain cases a direct access to the bearing unit for vibro-measurements is impossible or a high vibration from the mechanisms operating next to it can take place. This method is labor-intensive and requires special equipment and high-qualified personnel.

This work suggests a method for the monitoring of technical condition of induction motor bearing units according to the spectral analysis of the consumed current. The current can be measured directly across the terminals of the electric motor and in the nearest electric enclosure. The spectral distribution of the consumed current is conditioned by the harmonic components of the magnetic induction in the air gap of the induction motor. In fact except the basic harmonic component the machines in their air gap have also a huge amount of highest harmonics of the magnetic field. These highest harmonic components are traditionally divided into time and space harmonics. The time harmonic components are defined by the spectral distribution of voltage and non-linear changes of machine shaft rotating torque and its rotation frequency. Space harmonics of the field in the air gap appear due to non-linear parameters of the machine and its constructive features. If the power of the motor is commensurable with that of the generator mostly taking place in autonomous networks (for example, in marine power plants) then non-sinusoidal field in the air gap causes non-sinusoidal form of the voltage across the machine terminals closing the currents of the highest harmonics through the load [3, 4]. The main space harmonic components are tooth harmonics, harmonics of MMF, harmonics caused with the non-linear parameters of the electric machine, combinative and technological harmonics. The latter are caused by the technological parameters – misalignment of rotor and stator, taper and elliptic type of the rotor, eccentric type of the stator bore, faults of the bearing units, faults of the rotor and stator windings.

The essence of the method is in detection of character frequencies in the spectrum of the supply current (voltage) of induction motor. Mechanical defects of the bearing races, rotary bodies and separators cause changes of its space position in the stator bore, periodic braking of the rotor, some changes in its angular frequency of rotation and angular acceleration. It results in the changes in the electromagnetic mutual operation of rotor and stator, oscillations of electromagnetic rotational torque [5, 6]. Thus the character frequencies appear within the spectrum of the consumed current, frequency and magnitude of these frequencies depend on the present technical condition of the bearing unit [1, 7, 8]. The frequency and magnitude of these harmonic components are the necessary diagnostic parameters [2, 9]. Modern achievements in measuring and microprocessing technologies give the opportunities of certain and accurate measurements and analysis of such harmonics having low amplitude (up to low percentage).

1. Mathematical modeling of the induction motor

The mathematical modeling has been realized on the basis of mathematical model of squirrel-cage induction motor (Figure 1) described in the system of mutually rotating axes of phase windings *A, B, C, a, в, c,* [5, 6]:

$$\begin{cases} u_A = R_A i_A + \frac{d\psi_A}{dt}; \\ u_B = R_B i_B + \frac{d\psi_B}{dt}; \\ u_C = R_C i_C + \frac{d\psi_C}{dt}; \\ 0 = R_a i_a + \frac{d\psi_a}{dt}; \\ 0 = R_b i_b + \frac{d\psi_b}{dt}; \\ 0 = R_c i_c + \frac{d\psi_c}{dt}, \end{cases} \tag{1}$$

where u – voltages;
R – resistances;
i – currents;
ψ –flux linkages of all stator and rotor phases.

The equation of rotor's movement:

$$J\frac{d\Omega}{dt} = M_{em} - M_{stat}, \tag{2}$$

where M – torque;
J – torque of inertia;
Ω – angular speed.

Flux linkages of all loops of the motor is written down:

$$\begin{cases} \psi_A = L_A i_A + M_{AB} i_B + M_{AC} i_C + M_{Aa} i_a + M_{Ab} i_b + M_{Ac} i_c; \\ \psi_B = M_{BA} i_A + L_B i_B + M_{BC} i_C + M_{Ba} i_a + M_{Bb} i_b + M_{Bc} i_c; \\ \psi_C = M_{CA} i_A + M_{CB} i_B + L_C i_C + M_{Ca} i_a + M_{Cb} i_b + M_{Cc} i_c; \\ \psi_a = M_{aA} i_A + M_{aB} i_B + M_{aC} i_C + L_a i_a + M_{ab} i_b + M_{ac} i_c; \\ \psi_b = M_{bA} i_A + M_{bB} i_B + M_{bC} i_C + M_{ba} i_a + L_b i_b + M_{bc} i_c; \\ \psi_c = M_{cA} i_A + M_{cB} i_B + M_{cC} i_C + M_{ca} i_a + M_{cb} i_b + L_c i_c, \end{cases}, \tag{3}$$

where L – leakage inductance;
M – mutual inductance of stator and rotor loops.

In order to prove these assumptions this paper considers the results of mathematical modeling, calculations of magnetic fields and experimental examining of induction motors.

$$[\psi] = [LM]*[I], \tag{4}$$

where

$$[LM]=\begin{bmatrix} L_A, M_{AB}, M_{AC}, M_{Aa}, M_{Ab}, M_{Ac} \\ M_{BA}, L_B, M_{BC}, M_{Ba}, M_{Bb}, M_{Bc} \\ M_{CA}, M_{CB}, L_C, M_{Ca}, M_{Cb}, M_{Cc} \\ M_{aA}, M_{aB}, M_{aC}, L_a, M_{ab}, M_{ac} \\ M_{bA}, M_{bB}, M_{bC}, M_{ba}, L_b, M_{bc} \\ M_{cA}, M_{cB}, M_{cC}, M_{ca}, M_{cb}, L_c \end{bmatrix}, \quad (5)$$

$$[I]=\begin{bmatrix} I_A \\ I_B \\ I_C \\ I_a \\ I_b \\ I_c \end{bmatrix}. \quad (6)$$

The system of the equations (1) can be resolved concerning derivative of flux linkages in matrix form:

$$\tfrac{d}{dt}[\psi]=[U], \quad (7)$$

where

$$[U]=\begin{bmatrix} u_A - R_A i_A \\ u_B - R_B i_B \\ u_C - R_C i_C \\ -R_a i_a \\ -R_b i_b \\ -R_c i_c \end{bmatrix}. \quad (8)$$

Having resolved system (7) with (5), (6) and (8) we shall receive:

$$\frac{d}{dt}([LM]*[I])=[U]. \quad (9)$$

Having resolved system (9) concerning derivative currents, we shall receive:

$$\frac{d}{dt}[I]=[LM]^{-1}*[U], \quad (10)$$

where $[LM]^{-1}$ – inverse matrix [LM].

The influence of different kinds of bearing units faults on the distribution of harmonic components of currents consumed by electric motor was investigated on the basis of the developed mathematical model.

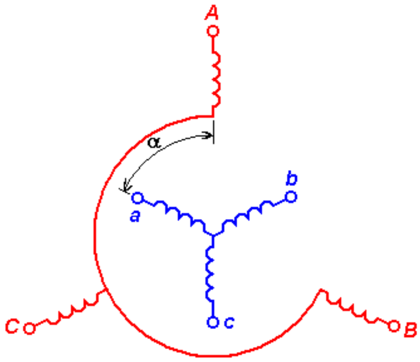

Fig. 1. **Model of the induction motor windings**

2. Calculations of magnetic fields of induction motor

For the investigation of the influence of different kinds of bearing units on the magnetic field pattern the field of the motor was calculated. While solving this task a standard program for the magnetic field calculation Quick Field has been applied [10]. With the help of the program the topology of the final elements of the considered magnetic circuit has been built, boundary conditions has been set, calculation and visualization of the investigated parts of motor have been realized. Models imitating the rotor displacement resulted from the bearings faults have been developed for the investigation of bearings typical faults influence on the field topography. As a result the pictures of magnetic field have been obtained demonstrating the distortions of it caused by the faults (Figure 2).

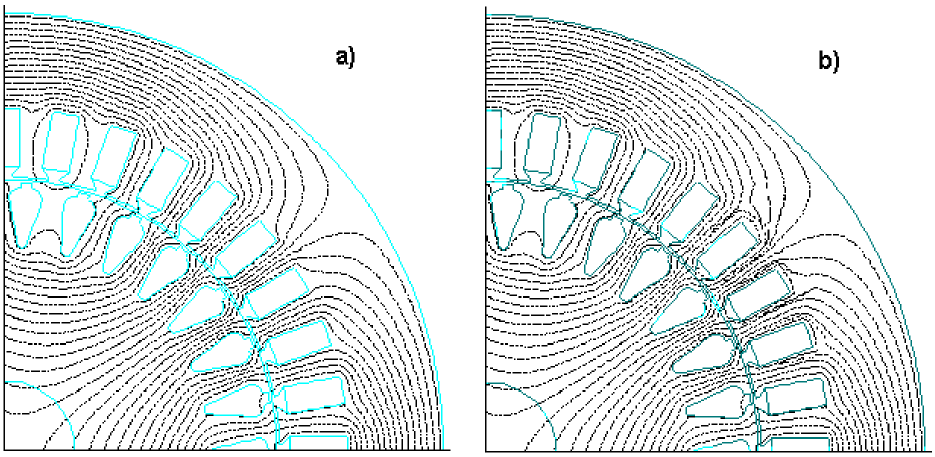

Fig. 2. **Calculation of magnetic field of induction motor (pole distribution – τ):**
a) motor without a fault; b) motor with a fault in bearing unit.

On the basis of the considered calculation results the harmonics spectrum of the induction in motor air gap was analyzed. Figures demonstrate the calculations of induction distribution in air gap transversely to the motor axis without faults (Figure 3) and with faults (Figure 4) in the bearing unit.

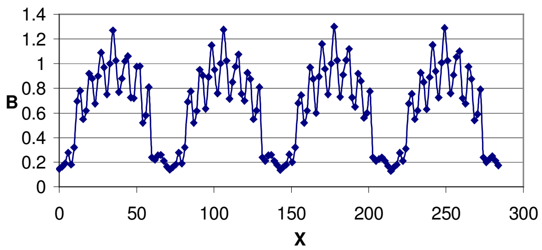

Fig. 3. **Induction distribution in the motor air gap with the faults**

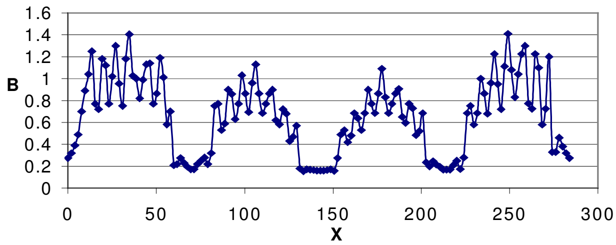

Fig. 4. **Induction distribution in the motor air gap without the faults**

Figure 5 demonstrates the results of calculations of induction distribution in air gap along the axis direction for the case of fault presence in the right bearing unit (Figure 5).

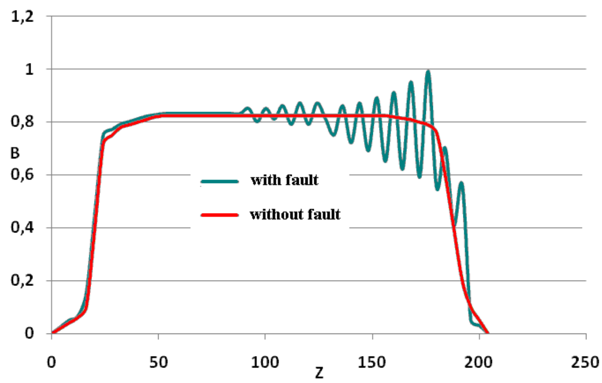

Fig. 5. **Induction distribution in air gap along the axis direction of the motor with and without fault in the bearing unit**

The results of magnetic field investigation clear demonstrate not only qualitative but also quantitative distortion of the field along the crosswise and lengthwise direction of the motor axis in the case of fault presence in the bearing unit. Distortion of the field results in the appearance of the highest harmonic components spectrum in the induction of motor air gap that in its turn causes the highest harmonics within the spectrum of the consumed current and voltage.

3. Experimental examining of the induction motor

The system for the monitoring of bearing units technical condition on the basis of electric current spectral analysis contains sensors for transformation of time and space harmonic parameters into electric signals, and analogue-digital converter connected to calculating equipment with correspondent software. The scheme of the monitoring system is in Figure 6. The shaft of induction motor 1 is connected with the compressor 5 shaft that is a load of the motor 1. Disc 3 is fixed on the shafts of the machines 1 and 5. Disc 3 has 36 magnetic marks 10 with an even step for the sensor of angular rotor position and one magnetic mark for sensor 4 – for the initial angular rotor position. The current consumed by the induction motor is controlled with the help of three sensors of current 6.

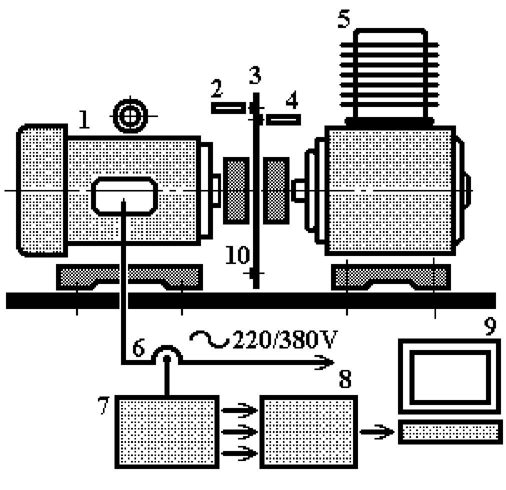

Fig. 6. **The scheme of experimental installation for the monitoring of bearing units of electric motor:**
1 – three-phase induction motor; 2 – sensor of the angular rotor position; 3 disc with magnetic marks; 4 – sensor of the initial angular rotor position (initial point); 5 – piston-type compressor – load of the induction motor 1; 6 – sensors of the current; 7 – filter of the lower frequencies; 8 – analogue-digital converter (ADC) with input commutator; 9 – computer with software; 10 - magnetic marks.

Signals from them are supplied to the filter of low frequencies 7. Filter 7 retains electric signals with frequencies lower than 400 Hz. After it the filtered signals rum to analogue-digital converter with commutator on the input. From its output the numbered (digital) signal goes to computer 9. The computer also gets frequency (digital) signals from sensors 2 and 4. The computer's software includes the program of spectral analysis. The information supplied to the computer is analyzed defining the frequency spectrum of the signals. The information is stored for comparison with the results of the further measurements. The spectrum of the consumed current is of complex type having a lot of frequencies. But the most interesting tendency is changing of character frequencies. Appearance of new frequencies gives the information for judgment about the technical condition of the bearing unit [11].

Results and discussion

The operating rolling bearing produces mechanical vibrations, being divisible by the basic frequency of three-phase electric motor rotation. These frequencies are called character.

$$f = k_1 \cdot f_n, \tag{11}$$

where f – typical (character, distinctive) frequencies;
$k_1 = 1\ldots5$ – coefficients;
f_n – typical (character, distinctive) frequencies with the presence of defects in the bearing elements.

For the rolling bearings four character frequencies could be calculated, the amplitudes of them for the serviceable and faulty bearings differ a lot [12]. Frequency of rolling bodies movement along the outside race

$$f_{n\ out} = (D_{int}/(D_{int}+D_{out}))\cdot N\cdot f_{\mathrm{r}}\,, \tag{12}$$

Frequency of rolling bodies movement along the inside race

$$f_{n\ int} = (D_{out}/(D_{int}+D_{out}))\cdot N\cdot f_r. \tag{13}$$

Frequency of rolling bodies rotation

$$f_{n\ blob} = (D_{out}/D_{blob})\cdot(D_{int}/(D_{int}+D_{out}))\cdot f_r. \tag{14}$$

Frequency of separator rotation

$$f_{n\ sep} = (D_{int}/(D_{int}+D_{out}))\cdot f_r, \tag{15}$$

where f_n – character frequencies with the presence of faults in the bearing elements;
D_{int} – diameter of the inside race;
D_{out} – diameter of the outside race;
N – amount of the rolling bodies;
D_{blob} – diameter of the rolling bodies;
f_r – frequency of the shaft rotation.

As an example a bearing of type 60305 will be considered, with the parameters: $D = 72$ mm; $d = 30$ mm; $B = 19$; $N = 8$; $D_{int} = 38.7$ mm; $D_{out} = 63.3$ mm; $f_r = 1420$ min^{-1}.

The character frequencies will be:

$$f_{n\ out} = 4311\ \text{Hz}; f_{n\ int} = 7049\ \text{Hz}; f_{n\ blob} = 2772\ \text{Hz}; f_{n\ sep} = 539\ \text{Hz}.$$

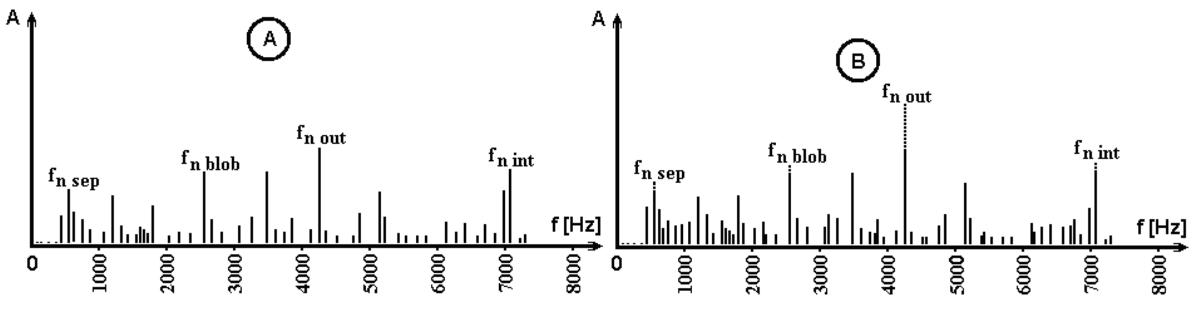

Fig. 7. **The spectrum of the current consumed by induction motor**

Figure 7 demonstrates spectrum of the current for serviceable (a) and faulty (b) bearing unit. Amplitude of the harmonics is on a per-unit basis (in reliable units). The basic unit is assumed as an amplitude of harmonic 4311Hz at the frequency of rolling bodies rotation along the outside bearing race of the serviceable electric motor $f_{n\ out}$. In the case of faulty electric motor the amplitude of all character frequencies increased for about 10-20 % that first of all informs on the weakening of lubricating regime. Increasing of the frequency $f_{n\ out}$. Amplitude is more noticeable signaling about a single defect on the outside bearing race. Having two faults gives a possibility of doubled frequency harmonic appearance 4311 x 2 = 8622 Hz. If, for example, the load of the induction motor is piston-type compressor (at the angular rotation frequency 1420 min^{-1}) lies within the range 23-24 Hz. Signals with this frequency are retained with low frequency filter 7 (Figure 6).

Figure 8 contains a photo of the experimental installation.

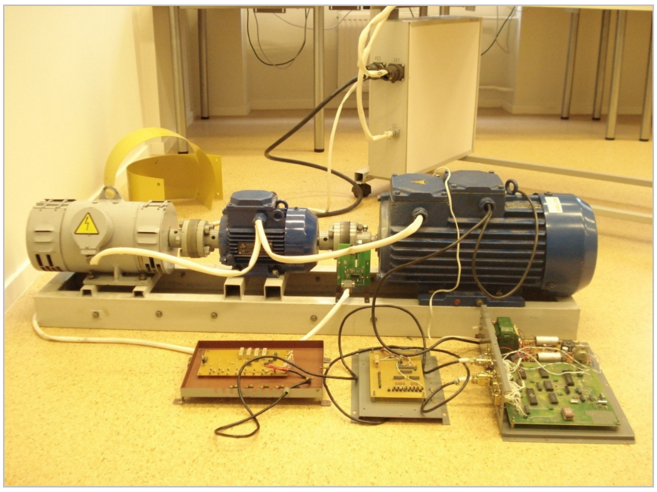

Fig. 8. **Experimental installation**

Conclusions

1. The suggested methodology allows diagnostics of the bearing units of induction machines according to the spectrum of the consumption current. The reference model is a spectrum of the current consumed in a faultless electric motor or a mathematic model of magnetic field in the air gap of induction motor.
2. The increasing of character frequencies amplitudes generated in bearings is a diagnostic parameter reliable for 7-10%.

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