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Simulation of three-phase induction motor different bearing faults in Matlab Simulink environment

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Abstract. The article describes the simulation of bearing failures in a three-phase induction motor in the Matlab Simulink environment. According to statistics most of induction motor faults happens due to bearings destruction or stator winding insulation degradation. Vibration analysis is often used to diagnose the bearings condition. This paper considered the model designing principles of different types of bearing faults of induction motor.

1. Introduction

Today, the induction motor (IM) is the most common type of electric machine. This type can be found in all types of industries. Examples are used the oil industry, heat-generating companies, electric power industry, etc. In industrial practice, there are known cases an IM failure due to electrical and mechanical types of breakdowns. Mechanical failures are of the greatest interest. This type of fault is common in manufacturing plants due to difficult operating conditions and improper motor service. In scientific and engineering practice, IM diagnostic algorithms are tested on test-benches using real faulty equipment, which is not always available for use. Testing on mathematical models can be a preliminary step in diagnostic algorithms debugging [1-3]. This type of debugging allows to make additional adjustments of microcontroller program before field experiments. Therefore, the development of IM failure models is one of the most important tasks in the overall algorithms development for motor diagnostics.

2. Studying of the problem

In practice, the dynamic fault models are commonly used for testing diagnostic algorithms. For this reason, a system of dynamic equations describing electromagnetic and electromechanical processes in the motor is used to build an IM model (1) [1, 2].



$$\left\{ \begin{array}{l} \frac{di_{s\alpha}}{dt} = \frac{1}{L_e}(U_{s\alpha} - R_e i_{s\alpha} + K_r Z_p \omega_r \psi_{r\beta} + K_r A_r \psi_{r\alpha}); \\ \frac{di_{s\beta}}{dt} = \frac{1}{L_e}(U_{s\beta} - R_e i_{s\beta} + K_r Z_p \omega_r \psi_{r\alpha} + K_r A_r \psi_{r\beta}); \\ \frac{d\psi_{r\alpha}}{dt} = R_r A_r i_{s\alpha} - A_r \psi_{r\alpha} - Z_p \omega_r \psi_{r\beta}; \\ \frac{d\psi_{r\beta}}{dt} = R_r A_r i_{s\beta} - A_r \psi_{r\beta} - Z_p \omega_r \psi_{r\alpha}; \\ M_e = \frac{3}{2} Z_p K_r (\psi_{r\alpha} i_{s\beta} - \psi_{r\beta} i_{s\alpha}); \\ \frac{d\omega_r}{dt} = \frac{1}{J_e} (M_e - M_c); \\ \theta = \arctan \frac{\psi_{r\beta}}{\psi_{r\alpha}}; \end{array} \right. \quad (1)$$

where $\psi_{r\beta}$, $\psi_{r\alpha}$ - rotor flux in $\alpha \beta$ coordinates [Wb]; $\psi_{s\beta}$, $\psi_{s\alpha}$ - stator flux in $\alpha \beta$ coordinates [Wb]; $i_{r\beta}$, $i_{r\alpha}$ - rotor current in $\alpha \beta$ coordinates [A]; $i_{s\beta}$, $i_{s\alpha}$ - stator current in $\alpha \beta$ coordinates [A]; $U_{s\beta}$, $U_{s\alpha}$ - IM stator voltage in $\alpha \beta$ coordinates [V]; R_r and R_s - rotor and stator resistance [Ohm]; M_e - electromagnetic torque [Nm]; M_c - load torque [Nm]; θ - rotor flux position angle [rad]; Z_p - pole pairs; L_s - stator inductance [H]; L_r - rotor inductance [H]; L_m - magnetization inductance [H]; $K_r = \frac{L_m}{L_e}$, $R_e = R_s + K_r^2 L_e$, $L_e = L_s - \frac{L_m^2}{L_r}$, $A_r = \frac{L_m}{L_e}$ - accepted designations.

The Matlab Simulink SimPowerSystems library has an IM with squirrel-cage rotor model. The model is used in this paper. The IGBT model of an inverter with a scalar control system is used as a source for the motor (fig. 1).

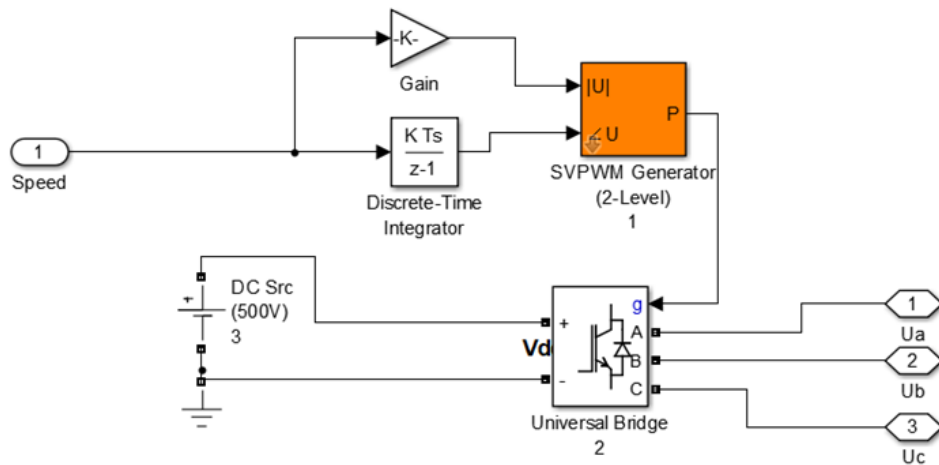


Figure 1. IGBT inverter model with scalar control system as source for induction motor

Vibration on the IM shaft occurs due to various bearing defects such as inner and outer

raceway ring fault or bearing balls destruction [3, 4]. The bearing vibration characteristic frequency corresponds to each of the fault types:

$$\begin{cases} f_b = \frac{D_c^2}{D_b^2} f_r (1 + \frac{D_b^2}{D_c^2} \cos^2 \beta); \\ f_i = \frac{N_b}{2} f_r (1 + \frac{D_b}{D_c} \cos \beta); \\ f_o = \frac{N_b}{2} f_r (1 - \frac{D_b}{D_c} \cos \beta); \end{cases} \quad (2)$$

where f_o – vibration characteristic frequency of bearing with outer raceway ring fault [Hz], f_i – vibration characteristic frequency of bearing with inner raceway ring fault [Hz], f_b – vibration characteristic frequency of bearing with ball destruction fault [Hz], N_b – number of bearing balls; D_c – bearing separator diameter [mm], D_b – ball diameter [mm], D_i – inner raceway ring diameter [mm], D_o – outer raceway ring diameter [mm], β – ball contact angle, f_r – rotor speed [Hz].

Vibration on the motor shaft can be simulated using an additional pulsing load torque, which equals to:

$$M_{bf} = M_c (1 + \cos 2\pi f_c t) \quad (3)$$

where M_{bf} – additional load torque, which is the equivalent of vibration for various bearing faults, M_c – torque magnitude, f_c – vibration characteristic frequency of bearing fault, t – time [s].

The torque amplitude depends on the degree of bearing destruction. Also, the pulsation value depends linearly on the load torque. Additional load torque computing in Matlab Simulink depicted in figure 3.

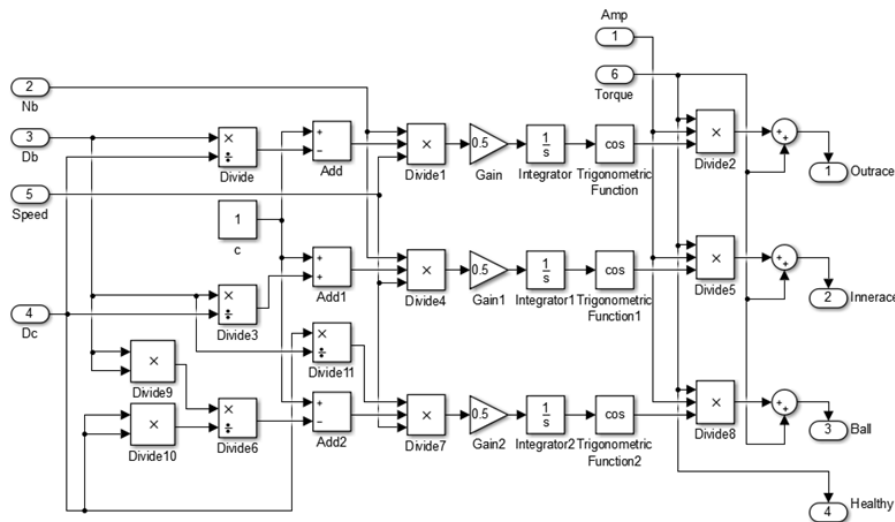


Figure 2. Additional load torque computing in Matlab Simulink environment

It is assumed that the motor is operated with a rated load of 14 [Nm], so a healthy motor is loaded with a high torque value. If there are bearing faults, the load torque is added to the load

torque calculated using the equation 2. For each type of fault, the frequency of the additional torque caused by a specific bearing fault is different. Calculation of the load torque in a unit of a faulty bearing is performed in the block (*Load*). The input unit receives the bearing parameters (N_b , D_c , D_b), the relative frequency amplitude plus the amplitude of the faulty bearing (Amp) rated load torque ($Torque$) and the rotor speed of the IM ($Speed$). The output parameter is the torque of load: in case of the faulty outer bearing race (*Outer*); defective inner race (*Inner*); bearing fault ball (*Ball*).

It is known that vibration on the shaft of an asynchronous motor causes the growth of harmonics at the frequencies at which it occurs. This feature is the basis of the method for diagnosing the state of an IM using spectral analysis of the stator current. Therefore, we can check the adequacy of the model by modeling this diagnostic method at Matlab. The magnitude of the stator current vector (or Park vector) is calculated for further spectral analysis. The complex model includes electric drive systems with a healthy motor and motors with various bearing defects (fig. 3). The stator current Park vector magnitude is calculated and recorded during the simulation in each model subsystem.

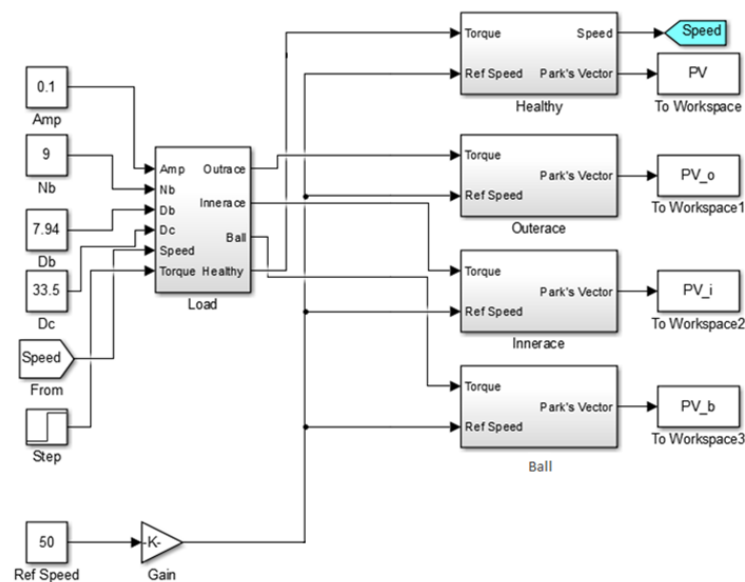


Figure 3. Complex model in Matlab Simulink environmentt

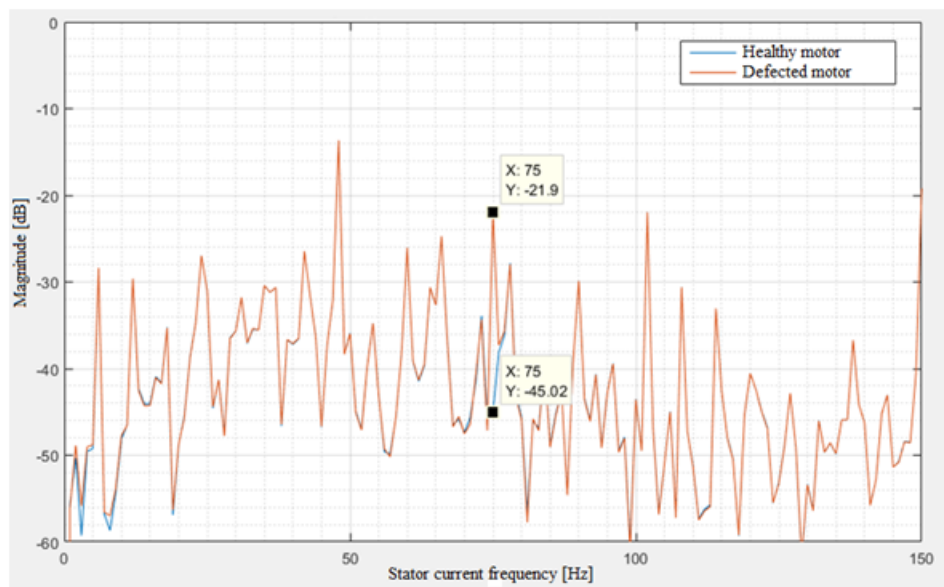
3. Simulation results

The rotor speed at rated load was 137 rad/s. Calculated frequencies that simulate faults associated with the bearing faults equals (2): $f_i = 121.37$ [Hz]; $f_o = 74.96$ [Hz]; $f_b = 43.54$ [Hz]. Spectral analysis of the Park vector was performed using the Matlab script (fig.4, 5, 6). The using motor parameters, which are presented in table 1. The parameters of the simulated bearing are shown in table 2.

As a result of spectral analysis of the stator current vector magnitude in the presence of a defect in the outer ring bearing, an increase of 23.1 dB in the harmonic component of 75 Hz was detected, which in turn coincides with the frequency of vibration on the rotor shaft. Therefore, this component, when diagnosing the motor, clearly indicates the presence of a fault associated with the outer ring bearing.

Table 1. Parameters of IM.

Notation	Parameter	Values
P	Rated power	2.2 [kW]
n	Rated speed	1470 [rpm]
R_r	Rotor resistance	3.297 [Ohm]
R_s	Stator resistance	3.6012 [Ohm]
L_s	Stator inductance	0.1769 [H]
L_r	Rotor inductance	0.1769 [H]
L_M	Mutual inductance	0.168 [H]
J	Rotor inertia	0.035 [kg · m ²]
Z_p	Number of pole pairs	2

**Figure 4.** Spectrogram of current vector for motor with outer raceway ring bearing defect**Table 2.** Parameters of IM.

Notation	Parameter	Values
D_o	Outer ring diameter [mm]	52
D_t	Inner ring diameter [mm]	25
D_c	Bearing separator diameter	33.5
D_b	Ball diameter [mm]	7.94
N_b	Number of bearing balls	9
β	Ball contact angle [rad]	0

Similarly, the harmonic component of 122 Hz increased by 15.3 dB (fig. 5). The growth of

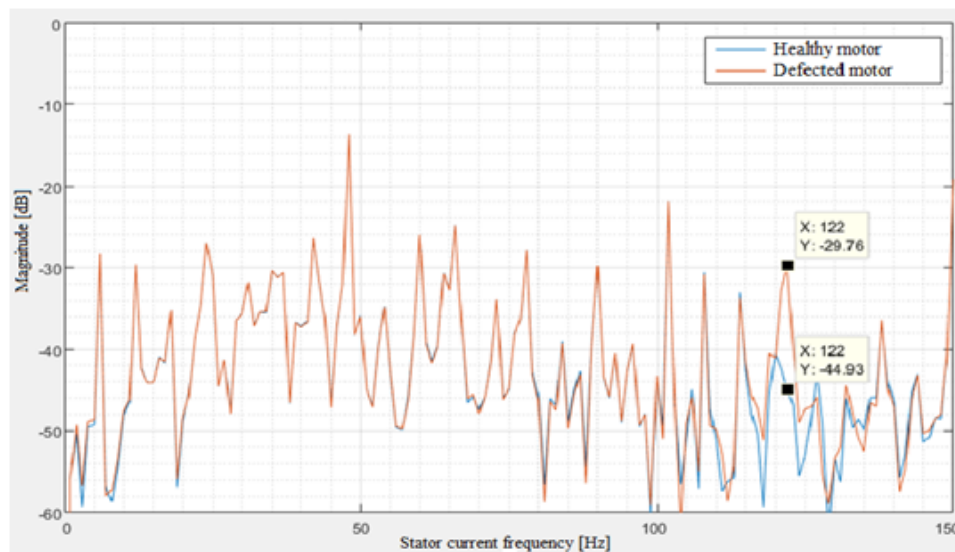


Figure 5. Spectrogram of current vector for motor with inner raceway ring bearing defect

this harmonic is caused by an inner raceway defect of bearing. A 10 dB increase in the harmonic component of 44 Hz was also detected when modeling a motor with defective bearing balls (fig. 6).

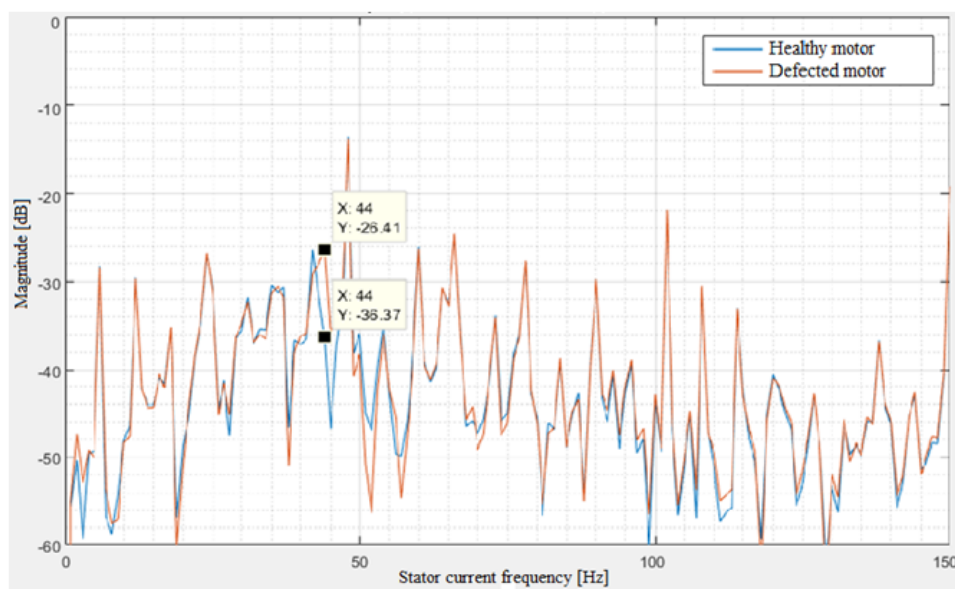


Figure 6. Spectrogram of current vector for motor with ball bearing defect

4. Summary

As a result, all simulated bearing failures were detected on the current vector spectrogram at the corresponding frequencies. This means that the simulated faults adequately reflect real events. In the future, a full-scale model will be designed on the basis of laboratory-bench, which will include an IM with the possibility of replacing bearings with faulty ones. It is possible that

the developed model in Matlab Simulink will be corrective with experimental results. Proposed model allows to test IM diagnostics algorithms in Matlab Simulink environment. The model can also be used as a part of semi-natural fault simulation laboratory bench that includes the test IM and direct current motor on the same shaft producing vibration torque corresponding to bearing fault.

It is assumed that the results of the work will be included in the training course of the new master's program "Conceptual Design and Engineering of Improving Energy Efficiency" for the training of engineering skills, scientific personnel and management personnel in the power industry, grid companies and related sectors [5].

Acknowledgments

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