A model-based method for bearing fault detection using motor current

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Abstract. Existing bearing fault diagnosis approaches utilize signal processing techniques in combination with vibration measurements. The common vibration measurement method, using accelerometer, has disadvantages such as position-constrains, high costs and external interferences. Meanwhile, the commonly used modelling methods of motor are not able to analyse both mechanic and electromagnetism simultaneously. For detecting the fault-related frequencies in motor current, a mathematical model is developed in this paper based on modified winding function approach (MWFA). The simulation results show that the fault-related characteristic frequencies can be exactly found in the spectrum results of motor current. The proposed method is proven to be feasible.

1. Introduction
Rolling bearing is an indispensable component in rotating electrical machines which are the most common prime machines in industrial processes. It can easily get failure under harsh working conditions that may lead catastrophic failures and costly downtime. Therefore, the condition monitoring and fault diagnosis of bearing has become a research hotspot for the guarantee of system safety and reliability.

Traditionally, most diagnosis methods are based primarily on vibration signal processing techniques. Dowling et al. [1] noted the point of entry and point of impact phenomenon, and illustrated that might be a potential idea for the fault severity quantitative analysis. Zhao et al. [2] applied the approximate entropy method and empirical mode decomposition to separate the entry-exit events and estimated the size of the spall-like fault. However, these methods are impracticable in actual manufacturing practice with following drawbacks: (1) external noise can easily interfere with vibration signals, (2) measurement results are highly dependent on the position of sensors, and (3) the equipment cost is high. Therefore, it is essential to detect bearing faults quantitatively with a non-intrusive and lower cost method.

Motor current signature analysis (MCSA) is a lower-cost, non-intrusive and effective technology for detecting bearing faults compared to the methods based on vibration signal. For instance, Schoen et al. [3] reported a relationship between vibration and current frequencies caused by developing faults in the bearings while using vibration monitoring and MCSA techniques. Blodt et al. [4] presented mathematical models for bearing fault detection using MCSA. Overall, stator current signal contains plenty of information which has the potential to be utilized in bearing fault diagnosis.
Bearings faults of motor lead to the periodic eccentricity of the rotor. Modified winding function approach (MWFA) is an effective and accurate method that provides a computable way to calculate the inductance in the motor according to the distribution of the winding and the air-gap. Ghoggal et al. [5] and Pu Shi et al. [6] combined MWFA with the multiple coupled circuit model of motor to detect eccentricity fault and rotor fault respectively.

This paper devoted towards providing a new reliable model bearing fault diagnosis of motor by using motor current signal. Bearing faults are considered to be a series of time-variant rotor eccentricity that leads to variations of air-gap. According to MWFA, the variations of air-gap cause variations of self-inductance and mutual-inductance of stator and rotor, then lead to distortion of the stator current. The advantage of this method is the calculation speed which allows it to be utilized in industrial application.

2. Bearing Fault Characteristic Frequencies in Motor Current

The characteristic frequency $f_c$ can be found in the motor current. The characteristic frequencies are functions of the bearing geometry and the mechanical rotor frequency $f_r$. The number of balls is denoted as $N_b$, the point of contact between a ball and the raceway is characterized by the contact angle $\beta$, $D_b$ and $D_c$ are the diameter of ball and the cage respectively. For outer raceway defects, $f_c$ takes the following expressions:

\[
 f_c = \frac{N_b}{2} f_r \left(1 - \frac{D_b}{D_c} \cos \beta \right) \tag{1} 
\]

The vibration frequencies can be approximated for most bearings with between 6 and 12 balls by:

\[
 f_o = 0.4N_b f_r \tag{2} 
\]

where, in an asynchronous motor, $f_r$ can be expressed as the following expression:

\[
 f_r = \frac{(1-s)}{p} f_s \tag{3} 
\]

where $f_s$ is the electrical stator supply frequency.

The generation of rotating eccentricities which occurs at bearing fault characteristic frequency $f_c$, leads to periodical changes in the machine inductances. This will produce additional frequencies $f_{bf}$ in the stator current, which is given by:

\[
 f_{bf} = |f_c \pm kf_s| \tag{4} 
\]

where $k=1,2,3, \ldots$

3. Modelling Method

3.1. Transient Model of the Induction Motor

An electromechanical coupling system can be represented as a series of equations, including voltage equations, flux equations and torque equations. And the following assumptions should be considered initially for the model of the induction motor:

(1) The air-gap is uniform and smooth;
(2) The eddy current, friction, windage losses and skin effect are neglected;
(3) Magnetic saturation is neglected and the permeance of the iron is infinite.
Considering a three-phase voltage source as a power supply, the machine equation can be written as (5). Where \( \mathbf{u} \) is the voltage matrix, \( \mathbf{L} \) is the inductance matrix, \( \mathbf{i} \) is the current matrix, \( \mathbf{R} \) is the resistance matrix of stator and rotor winding, \( T_e \) is the electromagnetic torque produced by supply voltage, \( J \) is the moment of inertia of the shaft assembled with rotor, \( \omega \) is the angular velocity of rotor, \( R_w \) is the rotating drag coefficient of rotor, \( T_m \) is the mechanical load coursed by external factors and \( P \) is the pole pairs of induction motor.

\[
\begin{align*}
\mathbf{u} &= \mathbf{L} \frac{d\mathbf{i}}{dt} + \mathbf{i} \frac{d\mathbf{L}}{dt} + \mathbf{iR} \\
T_e &= J \frac{d\omega}{dt} + R_w \omega + T_m = \frac{1}{2} P i^2 L_i \\
\frac{d\theta}{dt} &= P \omega
\end{align*}
\]

(5)

3.2. Calculation of time-varying inductances

The modified winding function approach (MWFA) is the basis to calculate all inductances for the induction machine. This method makes a sweep along the face of the stator and rotor of any position motor coil in the slots. The mutual inductance between any two windings \( i \) and \( j \) in any electric machine can be developed by:

\[
L_{ij}(\theta, \phi) = \mu_0 r l \int_0^{\pi} \int_0^{2\pi} n_i(\theta, \phi) M_j(\theta, \phi) g^{-1}(\theta, \phi) d\phi
\]

(6)

where: \( \mu_0 \) is the permeability of free space, \( l \) is the machine length, \( r \) is the mean radius of the air-gap. \( g^{-1}(\theta, \phi) \) is the inverse air-gap function which have been calculated in Section 2. The terms \( n_i(\theta, \phi) \) and \( M_j(\theta, \phi) \) are the distribution function and the modified winding function in windings \( i \) and \( j \) respectively.

The modified winding function \( M(\theta, \phi) \) can be calculated by:

\[
M(\theta, \phi) = n(\theta, \phi) - \langle M(\theta, \phi) \rangle
\]

(7)

where:

\[
\langle M(\theta, \phi) \rangle = \frac{1}{2\pi} \int_0^{2\pi} n(\theta, \phi) g^{-1}(\theta, \phi) g(\theta, \phi) d\phi
\]

(8)

\[
\langle g^{-1}(\theta, \phi) \rangle = \frac{1}{2\pi} \int_0^{2\pi} g(\theta, \phi) d\phi
\]

(9)

3.3. Air-gap Function

The outer race defect can be assumed to be located at the angular position \( \phi = 0 \). When there is no contact between a ball and the defect, the rotor is perfectly cantered. In this case, the air-gap length \( g \) is supposed to take the constant value \( g_0 \), neglecting rotor and stator slotting effects. On the other hand, the contact between a ball and the defect leads to a small movement towards the rotor centre on the stator reference frame (Shown in Fig. 1) every \( t = kf_0 \) (with \( k \) integer). At the same time, the air-gap length can be approximated by \( gd(1 - e \cos \phi) \), where \( e \) is the relative degree of eccentricity. The phenomenon is a periodic signal that represents a parabolic shape.
These considerations lead to the following expression for the air-gap length using the Fourier series:

\[ g(\phi, \theta) = g_0 \left[ 1 - e_0 \cos(\phi) \left( 2 \sum_{k=1}^{\infty} \frac{\sin(k \alpha \pi)}{k} \cos(k \theta) \right) \right] \]  

(10)

where \( e_0 \) is the relative degree of eccentricity introduced by the outer race defect, \( k=1, 2, 3, \ldots \).

4. Simulation Results
The studied machine is a three-phase two-pole induction motor with 6203 bearings. Floated star connection is considered for both rotor and stator windings. The Rated power is 0.25 kW, input voltage is 380 V, number of poles are 2, number of stator and rotor slots are 24 and 18 respectively, the length of stator stack is 60 mm, inner radius of stator is 76 mm and the length of air-gap is 0.3 mm.

Fig. 2 shows the current signal IM under healthy condition. From \( t=1.0 \) s to \( t=2.0 \) s, a \( T_L=0.2 \) Nm constant external load is applied followed by a \( T_L=0.5+0.5 \sin(20\pi t) \) alternate load from \( t=2.0 \) s to \( t=3.0 \) s, and after that the power supply is switched off. The simulation below is performed in MATLAB.
5. Conclusion
This paper has proposed a new model-based approach to explore and verify the potential of bearing fault diagnosis by using motor current signals. The air-gap variation is described as the formula according to the bearing fault. By the use of MWFA, the bearing fault-related motor current which is distorted by the variation of air-gap are calculated accurately and effectively. The simulation results show that the bearing fault is the main factor of the distortion of motor current.

In the future, the amplitude of the motor current should be calculated to test the potential of application for quantitative diagnosis of bearing fault. Moreover, further simulation and experiments should be carried out to verify the robustness of the proposed method.

Figure 2. Simulated current signal.

Figure 3. Current spectrum in fault case with 2% eccentricity degree.
Table 1. Theoretical values of fault characteristic frequencies

| Harmonic frequencies | Outer raceway fault (Hz) |
|----------------------|--------------------------|
|                      | 2003 rpm (s=0.038)       | 1450 rpm (s=0.052) |
| $k=1$                |                          |
| $f_1$                | 67.65                    | 48.62               |
| $f_2$                | 137.05                   | 99.62               |
| $k=2$                |                          |
| $f_3$                | 169.99                   | 122.74              |
| $f_4$                | 239.39                   | 173.74              |
| $k=3$                |                          |
| $f_5$                | 272.34                   | 196.85              |
| $f_6$                | 341.74                   | 247.85              |

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