Diagnostics of Faults In Multi-Phase Induction Motor Using Wavelet Transforms

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ABSTRACT

Induction machines play a vital role in industry and there is a strong demand for their reliable and safe operation. Faults and failures of induction machines can lead to excessive downtimes and generate large losses in terms of maintenance and lost revenues. Fault diagnosis of the electrical machines can significantly reduce the costs of maintenance by allowing the early detection of faults. This article presents off identifying induction motor rotor and stator faults using continuous and discrete wavelet transform. Faults are simulated by the mathematical model of the five phase induction machine using MATLAB/SIMULINK.

INTRODUCTION

Three-phase squirrel cage induction motors are commonly used in industrial applications in a wide range of fields, due to their simple and robust structure and low manufacturing cost. The reliability of an induction motor is of overriding importance for commercial and industrial applications also it is employed in the nuclear field and in the military industry. A very important fact that concerns the induction motor drive systems is the one related to the fast way in which every small defect is spotted right at the beginning. This will help to prevent accidents that could have led to major consequences in terms of energy saving and safety. The fault percentages and simplified faults in the induction motors are as shown in Figures. 1 and 2, where a diagram containing the frequency regarding possible defects from induction motors are presented.

Fig. 1: Induction motor fault percentages
Fig. 2: Simplified fault in the induction motors

The induction motor's broken bars can be detected using methods which are recommended in different works, for instance, we can use the mechanical vibration analysis method (Mori, D and T. Ishikawa, 2005), detection using air-gap torque spectra (Vinod V Thomas., Krishna Vasudevan, and V. Jagadeesh Kumar, 2003), spectral components study of angular speed signal (Media, M., F. Martin, Aurelian Crăciunescu and A. Rodriguez, 2012). The last method has a disadvantage as in (Watson, J.F and N.C.Paterson, 1998). Therefore, the stator current becomes a parameter often used for asynchronous motor fault detection (Bellini, A., F. Filippetti, G. Franceschini, C. Tassoni et.al, 2000). If the rotor bars break, they will produce a disturbance in the magnetic field of the machine’s air gap, resulting in the appearance of harmonics with certain frequencies in the machine’s stator current. The frequencies of these harmonics depend on the “s” value of the machine and on the “f” frequency of voltage power supply (Blodt, M., M. Chabert, J. Regnier, J. Faucher, 2006). The current from the induction motor stator was used for fault diagnosis of the rotor bars in many works, works based on Park’s vector analysis (Benouzza, M., M. Drif, A.J. Marques Cardos and J.A. Dente, 1999), or spectral analysis of the stator current with Fourier transform (Abdelkader Mellakhi, Noureddine Benouzza, Azzedine Bendiardellah, 2010). Works in this specific field have presented different procedures in identifying the broken rotor bars and they all made use of the waveform analysis of the stator current. In (Jusso T. Olkkonen, 2011, Ahamed, S.K., S. Karmakar, M. Mitra, S. Sengupta, 2010) it is clear that we are dealing with broken bars, since a Wavelet Transform (WT) has been used to measure (approximately and in detail) the levels of energy belonging to the stator current signal wavelet decomposition. In (Antonino, J.A., M. Riera, J. Roger-Folch and V. Climente, 2004, Mehala, N and R. Dahiza, 2009, Toshiji Kato., Kaoru Inoue, Daisuke Okuda, 2009) signals of coefficients are analysed, signals that resulted from the start-up current decomposition with DWT, in the broken bar diagnosis.

Mathematical Model For Fault Simulation of Five Phase Induction Motor:

The well-known space vector and d–q models of three phase machines are only special cases of the universal n phase machine models. Since the phase-variable model of a physical multiphase machine gets transformed using a mathematical transformation, the number of variables before and after transformation must remain the same, that means a n-phase machine will have n new stator currents (stator voltage, stator flux) components after the transformation. An n-phase symmetrical induction machine, such that the spatial displacement between any two consecutive stator phases equals α=2π/n, is considered. It is assumed that the windings are sinusoidally distributed, so that all higher spatial harmonics of the magneto-motive force can be neglected. The phase number n can be either odd or even. It is assumed that, regardless of the phase number, windings are connected in star with a single neutral point. The machine model in original form is transformed using decoupling (Clarke’s) transformation matrix (White, D.C and H.H. Woodson, 1957), which replaces the original sets of n variables with new sets of n variables. Decoupling transformation matrix for an arbitrary phase number n can be given in power invariant real or complex matrix transformations, resulting in corresponding real or space vector models of the sign multi-phase machine. Decoupling transformation matrix for an arbitrary phase number n can be given in the power invariant form shown in equation: 1, where α=2π/n. The first two rows of the matrix define variables that will contribute to fundamental flux and torque production (α–β components; stator to rotor coupling appears only in the equations for α–β components). The final two rows set
the two zero sequence components are excluded for all odd phase numbers \( n \). In between, there are \( x-y \) components.

\[
\begin{bmatrix}
    v_q \\
v_d \\
v_x \\
v_y \\
\theta_x
\end{bmatrix} = \frac{2}{\sqrt{n}}
\begin{bmatrix}
    1 & \cos \alpha & \cos 2\alpha & \ldots & \cos n\alpha \\
    0 & \sin \alpha & \sin 2\alpha & \ldots & \sin n\alpha \\
    1 & \cos 2\alpha & \cos 4\alpha & \ldots & \cos 2n\alpha \\
    0 & \sin 2\alpha & \sin 4\alpha & \ldots & \sin 2n\alpha \\
    \sqrt{2} & \sqrt{2} & \sqrt{2} & \ldots & \sqrt{2}
\end{bmatrix}
\begin{bmatrix}
    v_a \\
v_b \\
v_c \\
v_d \\
v_e \\
v_f \\
v_n
\end{bmatrix}
\]

(1)

Equations for pairs of \( x-y \) components are totally decoupled from all the other components and stator to rotor coupling does not appear either (White, D.C and H.H. Woodson, 1957). These components do not contribute to torque production when the sinusoidal distribution of the flux around the air-gap is assumed. A zero-sequence component does not exist in any star-connected multiphase system without a neutral conductor for odd phase numbers, while only zero components can exist if the phase number is even. Since the rotor winding is short-circuited, neither \( x-y \) nor zero-sequence components can exist, nor needs one only to consider further on \( \alpha-\beta \) equations of the rotor winding. As the stator to rotor coupling takes place only in \( \alpha-\beta \) equations, rotational transformation is applied only to these two pairs of equations. Its shape is similar to a three-phase machine. Assuming that the machine equations are transformed into an arbitrary frame of reference rotating at angular speed \( \omega_r \), the model of a \( n \)-phase induction machine with sinusoidal winding distribution is given by,

Stator circuit equations:

\[
v_{ds} = R_s i_{ds} + \frac{d}{dt} \psi_{ds} - \omega_e \psi_{qs}
\]

(2)

\[
v_{qs} = R_s i_{qs} + \frac{d}{dt} \psi_{qs} - \omega_e \psi_{ds}
\]

(3)

Rotor circuit equations:

\[
v_{dr} = R_r i_{dr} + \frac{d}{dt} \psi_{dr} - (\omega_e - \omega_r) \psi_{qr}
\]

(4)

\[
v_{qr} = R_r i_{qr} + \frac{d}{dt} \psi_{qr} - (\omega_e - \omega_r) \psi_{dr}
\]

(5)

Flux linkage expressions in terms of the currents are

\[
\psi_{ds} = L_k (i_{ds} + i_{dr}) + L_m (i_{ds} + i_{dr})
\]

(6)

\[
\psi_{dr} = L_k (i_{dr}) + L_m (i_{ds} + i_{dr})
\]

(7)

\[
\psi_{qs} = L_k (i_{qs} + i_{qr}) + L_m (i_{qs} + i_{qr})
\]

(8)

\[
\psi_{qr} = L_k (i_{dr}) + L_m (i_{qs} + i_{qr})
\]

(9)

\[
\psi_{dm} = L_m (i_{ds} + i_{dr})
\]

(10)

\[
\psi_{qm} = L_m (i_{qs} + i_{qr})
\]

(11)

\[
i_{ds} = \frac{\psi_{ds} (L_{1r} + L_m) - L_m \psi_{dr}}{(L_{1r} L_{1r} + L_4 L_{1m} + L_{1r} L_{1m})}
\]

(12)

\[
i_{qs} = \frac{\psi_{qs} (L_{1r} + L_m) - L_m \psi_{qr}}{(L_{1r} L_{1r} + L_4 L_{1m} + L_{1r} L_{1m})}
\]

(13)
where \( L_m = (n/2) M \) and \( M \) is the maximum value of the stator to rotor mutual inductances in the phase variable model.

\[
T_c = P L_m \left( q_s i_{d r} - i_{d s} i_{q r} \right) \tag{16}
\]

\[
w_r = \int \frac{P}{2J} \left( T_c - T_L \right) dt \tag{17}
\]

Model equations of the components in equations: 14-15, torque equation: 16 and speed equation: 17 are identical for a three phase induction motor. In principle, the same control schemes applied to multi-phase induction motors as for as three-phase motors.

**Wavelet Transform:**

Wavelet Transform (WT) was developed as an alternative to short-time Fourier transform. WT calculates the dot product of the analysed signal and provides simultaneous information regarding frequency and time.

The wavelet transform equation:

\[
C(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \Psi \left( \frac{t - b}{a} \right) dt \tag{18}
\]

Where \( x(t) \) is the signal, \( a \) and \( b \) shows the wavelet scale and position, \( \Psi(t) \) is the wavelet.

A high scale corresponds to a low frequency stretched wavelet and a low scale wavelet corresponds to a high frequency compressed wavelet. In the Discrete Wavelet Transform case (DWT), filters having different cutoff frequencies are used to analyse the signal at different scales. The signal is passed through a series of high pass filters so that the high frequencies can be analysed. Subsequently, it is run through a series of low pass filters in order to examine the low frequencies. The high pass filter coefficients are marked with D (from detail...
coefficients) and the low pass filter coefficients are marked with A (from approximate coefficients). The low frequency band extends from zero to half the Nyquist frequency where Nyquist frequency is \( N = f_s/2 \) (f, - sampling frequency). After decomposing the signal, one can reconstruct and study in detail the constituent parts of the original signal (Szabó, L., J.B. Dobai and K.A. Bíró, 2004).

**Simulation Results and Discussion:**

In this paper, a five-phase squirrel cage induction motor rotor current is considered for analysis of stator faults as well as rotor faults conditions using wavelet transforms. Both Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT) has implemented for normal and fault conditions. Motor parameters are presented in appendix. Under normal state (no fault condition) motor is operated at no load condition, at time \( t=1 \) s, 3 Nm load was introduced. The rotor current waveform for the normal operating state is shown in Figure. 4 and for 10% for short circuit fault on rotor shown in Figure. 5. From Figures 4 and 5 observed that, it’s hard to distinguish the faulty condition due to changes in current magnitude indicates either change in load as well as faults in stator windings or rotor bar or both. In case of faults, which causes an increment in rotor current which can be avoided, will affect the efficiency, lifetime of the machine, power factor and etc. In this paper symmetrical stator and rotor fault conditions were viewed and identified by wavelet analysis of rotor current analysis of the motor. In our case rotor current is considered, since symmetrical as well as asymmetrical faults in both stator and rotor can reflect all the phase of a rotor, which can be a good source for analysis. For analysis, 10 and 20 percent of short circuit fault in stator as well as rotor was introduced and CWT and DWT analysis are performed. Figures. 4(a) and 5(a) show the simulated response of phase A rotor current response of five-phase induction motor under healthy and fault conditions respectively.

**Fig. 4:** Simulated response of rotor current of five-phase induction motor under healthy condition

**Fig. 4(a):** Simulated response of phase a rotor current response of five-phase induction motor under healthy condition

**Fig. 5:** Simulated response of rotor current response of five-phase induction motor under 10% rotor shot circuit fault condition

**Fig. 5(a):** Simulated response of phase A rotor current response of five-phase induction motor under 10% rotor shot circuit fault condition

In Figure. 6, row 1 shows the responses of analysed rotor current waveform, row 2, column 1 has a power spectrum of the imaginary part of the signal, row 2 column 2 has a real part of the signal. Row 3, column 1 has
an angular power spectrum and row 3 column 3 has a frequency spectrum of the motor. The power band at the value of 18337.4 has the lower energy level in imaginary part and higher energy level in real part.

Fig. 6: Simulated response of CWT analysis of five-phase induction motor in healthy condition.

Fig.7: Simulated response of 9 level haar wavelet decomposition of five-phase induction motor under healthy condition
**Fig. 8:** Histogram waveform of 9 level decomposition of haar wavelet of five-phase induction motor under 10% healthy condition.

**Fig. 9:** Histogram waveform of 9 level decomposition of synthesized haar wavelet of five-phase induction motor under healthy condition.

**Fig. 10:** Simulated response of CWT analysis of five-phase induction motor under 10% rotor fault condition.

In Figure 10, row 1 shows the responses of analysed rotor current waveform, row 2, column 1 has a power spectrum of the imaginary part of the signal, row 2 column 2 has a real part of the signal. Row 3, column 1 has an angular power spectrum and row 3 column 3 has a frequency spectrum of the motor. From the Figure 10, the power band at the value of 18337.4 has an increment in energy level in imaginary part and decrement in energy level in real part.
Fig. 11: Simulated response of 9 level haar wavelet decomposition of five-phase induction motor under under 10% rotor fault condition

Fig. 12: Histogram waveform of 9 level decomposition of haar wavelet of five-phase induction motor under 10% rotor fault condition

Fig. 13: Histogram waveform of 9 level decomposition of synthesized haar wavelet of five-phase induction motor under 10% rotor fault condition
Fig. 14: Simulated response of CWT analysis of five-phase induction motor under 20% rotor fault condition.

In Figure. 14, row 1 shows the responses of analysed rotor current waveform, row 2 column 1 has a power spectrum of the imaginary part of the signal, row 2 column 2 has a real part of the signal. Row 3, column 1 has an angular power spectrum and row 3 column 3 has a frequency spectrum of the motor. From Figure. 14 it is
observed that the power band at the value of 18337.4 has a further increment in energy level as in imaginary part and decrement in higher energy level in real part as the percentage of amount of fault increased.

**Fig. 16:** Histogram waveform of 9 level decomposition of haar wavelet of five-phase induction motor under 20% rotor fault condition

**Fig. 17:** Histogram waveform of 9 level decomposition of synthesized haar wavelet of five-phase induction motor under 20% rotor fault condition

**Fig. 18:** Simulated response of CWT analysis of five-phase induction motor under 10% of stator fault condition. In Figure. 18, row 1 show the responses of analysed rotor current waveform, row 2, column 1 has a power spectrum of the imaginary part of the signal, row 2 column 2 has a real part of the signal. Row 3, column 1 has an angular power spectrum and row 3 column 3 has a frequency spectrum of the motor. From Figure.18 it is observed that, the power band at the value of 18337.4 has an increment in energy level as in imaginary part and decrement in higher energy level in real part, also there is a significant change (increment) in imaginary band and higher power scale 25709.3 and lower power scale 13079.3 bands are observed in stator fault condition.
Fig. 19: Simulated response of 9 level haar wavelet decomposition of five-phase induction motor under 10% stator fault condition

Fig. 20: Histogram waveform of 9 level decomposition of haar wavelet of five-phase induction motor under 10% stator fault condition

Fig. 21: Histogram waveform of 9 level decomposition of synthesized haar wavelet of five-phase induction motor under 10% stator fault condition
Fig. 22: Simulated response of CWT analysis of five-phase induction motor under 10% of stator fault condition.

Fig. 23: Simulated response of 9 level haar wavelet decomposition of five-phase induction motor under 20% stator fault condition.

In Figure. 22, row 1 show the responses of analysed rotor current waveform, row 2, column 1 has a power spectrum of the imaginary part of the signal, row 2 column 2 has a real part of the signal. Row 3, column 1 has an angular power spectrum and row 3 column 3 has a frequency spectrum of the motor. From Figure. 22 it is observed that, the power band at the value of 18337.4 has a further increment in energy level as in imaginary.
part and decrement in higher energy level in real part as the percentage of fault increases, also there is a significant change (increment) in imaginary band and higher power scale 25709.3 and lower power scale 13079.3 bands is observed in stator fault condition.

**Fig. 24:** Histogram waveform of 9 level decomposition of haar wavelet of five-phase induction motor under 20% stator fault condition

**Fig. 25:** Histogram waveform of 9 level decomposition of synthesized haar wavelet of five-phase induction motor under 20% stator fault condition

**Conclusion:**

Figure. 8 shows the decomposed current waveform of 9 level haar wavelet, synthesized signal and actual signal. From Figure. 9 the histogram of 9 levels decomposed signal, under healthy state the histogram has a symmetrical band with positive and negative side, from Figure. 9 the histogram of synthesized signal has lower bandwidth. In DWT, from Figures. 12, 13, 16 and 17, it is observed that in the rotor fault condition the bandwidth of the histogram of decomposed signal symmetrically increased and their magnitude as well, also for synthesized histogram waveform increment in negative bandwidth as well as magnitude has observed. From Figures. 20, 21, 24 and 25, it is observed that in the rotor fault condition the bandwidth of the histogram of decomposed signal symmetrically increased and its bandwidth but the magnitude remained small value. As for synthesized histogram waveform increment in positive bandwidth as well as magnitude has observed. Also for rotor fault conditions max peak value of histogram moved to the positive side of the band, while for stator fault conditions max peak maintained at 0 levels. At CWT, the energy level has change in particular power level in rotor fault condition, whereas for stator fault lower and the higher power band also has significant change, with that the percentage of fault as well as the location of the fault both can be detected for polyphase induction motors. Using fuzzy, neural, neuro-fuzzy, machine learning algorithms faulty conditions can be effectively classified.

**Appendix:**

**Induction Motor parameters**

- Rated power : 149 kW
- Rated voltage : 440V
- Rated speed : 3000 rpm
- Rated frequency : 50 Hz
- Stator Resistance : 6.03Ω
- Stator Inductance : 489.3mH
- Rotor Resistance : 6.085Ω
- Rotor Inductance : 489.3mH
- Mutual Inductance : 450.3mH
- Rotor inertia : 0.00488 Kg/m²
- No of poles : 4

**Nomenclature**

- B Friction coefficient
- J Moment of inertia
- Ls Stator leakage inductance
- Lr Rotor leakage inductance
- n Number of phases
- M Mutual inductance between stator and rotor
P \quad \text{Number of poles}

R_s \quad \text{Stator resistance}

R_r \quad \text{Rotor resistance}

\alpha \quad \text{Angular displacement between stator and rotor}

T_e \quad \text{Electromagnetic torque}

T \quad \text{Load torque}

\omega_e \quad \text{Rotor speed in electrical degrees}

\omega_m \quad \text{Rotor speed in mechanical degrees}

\theta \quad \text{Stator coordinate in electrical degrees}

\Psi \quad \text{Flux linkage}

d \quad \text{Direct axis}

q \quad \text{Quadrature axis}

v_{ds}, v_{qs} \quad \text{d \& q axis stator voltages}

v_{dr}, v_{qr} \quad \text{d \& q axis rotor voltages}

i_{ds}, i_{qs} \quad \text{d \& q axis stator currents}

i_{dr}, i_{qr} \quad \text{d \& q axis rotor currents}

REFERENCES


