International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Stator Inter-turn Fault Detection using MCSA

Rakesh A. Patel† and Md Aftab Alam†*

†Department of Electrical Engineering, UVPCE, Ganpat University, Ganpat Vidyanagar - 384012, Mehsana, Gujarat, India

Accepted 31 May 2015, Available online 02 June 2015, **Vol.5, No.3 (June 2015)**

Abstract

Condition monitoring of induction motor has become a necessity in today's competitive world of industries. Stator inter-turn fault is one of the most common faults occurring in the induction motor, not predicting it before it becomes severe, may lead to breakdown and loss of production. The stator current can be continuously monitored in order to predict any fault brewing in the stator windings. This paper presents a simple way of predicting the stator inter-turn fault by analyzing the spectrum of stator current. A mathematical model of three-phase induction motor is prepared in MATLAB – Simulink software from the well-known modeling equations of induction motor. The model is then run in healthy condition and fault condition of different number of inter-turns shorted. The current signal is acquired and analyzed by performing Fast Fourier Transformation (FFT) to predict the health condition of motor.

Keywords: *Condition monitoring, MCSA, FFT, Inter-turn fault.*

1. Introduction

Induction motor is the workhorse of industries. It is the single most widely used electrical machine worldwide and consumes the significant portion of energy (Esfahani, *et al*, 2014). Any breakdown of induction motor may bring the entire process to halt. Therefore the health of induction motor is of paramount importance with respect to the smooth running of plant and achieving production targets.

In fact, correct diagnosis and early detection of incipient faults result in fast unscheduled maintenance and short downtime for the process under consideration. They also avoid harmful, sometimes devastating, consequences and reduce financial loss. During the last years there has been a considerable amount of research into the creation of new condition monitoring techniques for induction motors and drives, overcoming the drawbacks of traditional methods. The topic is becoming far more attractive and critical as the population of electric machines has largely increased in recent years (Filippetti, *et al*, 2013).

Insulation system is potentially one of the intrinsically weakest components of an electrical machine, both mechanically and electrically; and in the earliest days of machine construction insulation faults were excessively frequent. However, modern techniques of winding manufacture, using thermosetting resin or vacuum pressure impregnated insulation, provide systems that are mechanically tough and electrically sound. Nonetheless, modern machine use drives insulation systems to their thermal, mechanical and electrical limits (Tanver, *et al*, 2008). Therefore, there are practical chances of stator winding faults.

There are many published techniques and many commercially available tools to monitor induction motors to insure a high degree of reliability uptime. In this context, a variety of sensors could be used to collect measurements from an induction motor for the purpose of failure monitoring. These sensors might measure stator voltages & currents, air-gap & external magnetic flux densities, rotor position & speed, output torque, internal & external temperature, case vibrations, etc (Didier, *et al*, 2006), (Douglas, *et al*, 2005). There are many prevalent approaches to the health diagnosis of induction motor including ordinary and intelligent approaches. The most famous ordinary approaches includes 'Thermal Monitoring', 'Air gap torque Analysis', 'Noise Monitoring', 'Vibration Analysis', 'Motor Current Signature Analysis', 'Partial Discharge Measurement', etc. The intelligent approaches in use are 'Expert System', 'Genetic Algorithm', 'Fuzzy logic', 'Artificial Neural Network' and 'Support Vector Machine'.

This paper describes the very common and simple way of detecting the stator fault with the help of Motor Current Signature Analysis (MCSA) technique. Section 2 presents the mathematical modeling of three-phase induction motor. In section 3 simulation of the model and data acquisition is explained. Section 4 describes the application of FFT in the MCSA approach of fault detection. Section 5 discusses the results obtained and the paper concludes with section 6.

*Corresponding author: **Md Aftab Alam**

2. Mathematical Modeling

The model of induction motor can be prepared with the help of its defining equations which have been presented by few eminent researchers like (Huang, *et al*, 2007), (Krause, *et al*, 2013), (Tallam, *et al*, 2002). By relating voltage, current, torque and flux linkage through some mathematical equations, the induction motor can be exactly modeled to give results like actual motor. In modeling, the help of different reference frame transformations is taken in order to simulate the situation according to the requirement.

The modeling of induction motor is carried out using MATLAB/SIMULINK software. The same is used here to analyze the induction motor in various conditions.

2.1 Modeling of healthy motor

The modeling equations of a healthy motor are represented as follows (Huang, *et al*, 2007), (Krause, *et al*, 2013), (Tallam, *et al*, 2002):

2.1.1 Equations of Stator

Equations of stator flux linkage are represented as follows:

$$\frac{d\lambda_{qs}}{dt} = v_{qs} - r_s i_{qs} - \omega\lambda_{ds} \tag{1}$$

$$\frac{d\lambda_{ds}}{dt} = v_{ds} - r_s i_{ds} + \omega\lambda_{qs} \tag{2}$$

Where,

v_{qs} = q-axis voltage of stator

v_{ds} = d-axis voltage of stator

λ_{qs} = q-axis flux linkage of stator

λ_{ds} = d-axis flux linkage of stato

r_s = stator resistance

i_{qs} = q-axis current of stator

i_{ds} = d-axis current of stator

ω = angular velocity of the reference frame

2.1.2 Equations of Rotor

Equations of rotor flux linkage are given as follows:

$$\frac{d\lambda_{qr}}{dt} = -r_r i_{qr} - (\omega - \omega_r)\lambda_{dr} \tag{3}$$

$$\frac{d\lambda_{dr}}{dt} = -r_r i_{dr} - (\omega - \omega_r)\lambda_{qr} \tag{4}$$

Where,

λ_{qr} = q-axis flux linkage of rotor

λ_{dr} = d-axis flux linkage of rotor

r_r = stator resistance

i_{qr} = q-axis current of rotor

i_{dr} = d-axis current of rotor

ω_r = speed of rotor

2.1.3 Equations of Current

The direct and quadrature axes currents for stator and rotor are represented by following equations:

$$i_{qs} = \lambda_{qs}a_1 - \lambda_{qr}a_2 \tag{5}$$

$$i_{ds} = \lambda_{ds}a_1 - \lambda_{dr}a_2 \tag{6}$$

$$i_{qr} = \lambda_{qr}a_4 - \lambda_{qs}a_2 \tag{7}$$

$$i_{dr} = \lambda_{dr}a_4 - \lambda_{ds}a_2 \tag{8}$$

Where constant coefficients are given as:

$$a_0 = L_s L_r - L_m^2 \qquad a_1 = \frac{L_r}{a_0}$$

$$a_2 = \frac{L_m}{a_0} \qquad a_3 = \frac{1}{L_{ls}}$$

$$a_4 = \frac{L_s}{a_0} \qquad a_5 = \frac{1}{L_{lr}}$$

L_s = stator self inductance

L_r = rotor self inductance

L_m = mutual inductance between stator and rotor

L_{ls} = leakage inductance of stator winding

L_{lr} = leakage inductance of rotor winding

2.1.4 Equation of Torque

The electro-mechanical torque is represented by following equation:

$$T_e = \frac{3}{2}\frac{p}{2}(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}) \tag{9}$$

Where, p is the number of poles of induction motor

2.1.5 Equation of Speed

The rotor speed is given as follows:

$$\frac{d\omega_r}{dt} = \frac{T_e - B_m\omega_r - T_l}{J} \tag{10}$$

Where,

T_l = load torque

B_m = coefficient of friction

J = moment of inertia

2.2 Modeling of motor with stator fault

Stator fault considered here is the inter turn short circuit fault; accordingly, the equations represented in section 2.1 for stator modeling get modified. The equations are modified considering the fact that when the turns are shorted, a parallel path for the fault current is created. This situation is modeled by incorporating a factor for turns fault which is the ratio of number of shorted turns to the total number of turns in healthy condition. The situation of stator fault is depicted in Fig. 1.

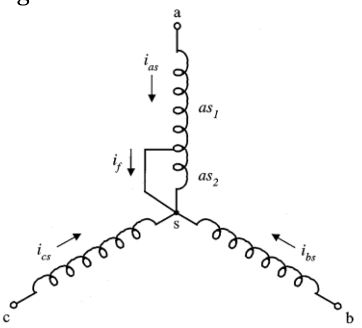

Fig.1 Stator fault condition

Including the effect of stator fault, the equations of stator are given as follows (Huang, *et al*, 2007), (Tallam, *et al*, 2002):

2.2.1 Equations of stator with inter-turn fault

The flux linkage equations of stator are modified due to inter-turn fault and are represented as follows:

$$\frac{d\lambda_{qs}}{dt} = v_{qs} - r_s i_{qs} - \omega\lambda_{ds} + \frac{2}{3}\mu r_s i_f \cos\theta \qquad (11)$$

$$\frac{d\lambda_{ds}}{dt} = v_{ds} - r_s i_{ds} + \omega\lambda_{qs} + \frac{2}{3}\mu r_s i_f \sin\theta \qquad (12)$$

Where

$$\mu = \frac{n_f}{n_s} = \frac{number\ of\ short-circuited\ turns}{number\ of\ total\ turns\ in\ healthy\ condition}$$

i_f is the fault current as shown in Fig. 1.

2.2.2 Equations of flux

The flux equation also gets modified as follows:

$$\frac{d\lambda_{as2}}{dt} = r_f i_f - \mu r_s (i_{ds}\cos\theta + i_{qs}\sin\theta - i_f) \qquad (13)$$

2.2.3 Equations of current

Similarly, the current equations are also modified due to stator fault and are represented as:

$$i_{qs} = \lambda_{qs}a_7 - \lambda_{qr}a_8 + (L_r a_{10} - L_m a_{11}) i_f \cos\theta \qquad (14)$$

$$i_{ds} = \lambda_{ds}a_7 - \lambda_{dr}a_8 + (L_r a_{10} - L_m a_{11}) i_f \sin\theta \qquad (15)$$

$$i_{qr} = \lambda_{qr}a_9 - \lambda_{qs}a_8 + (L_r a_{11} - L_m a_{10}) i_f \cos\theta \qquad (16)$$

$$i_{dr} = \lambda_{dr}a_4 - \lambda_{ds}a_2 + (L_s a_{11} - L_m a_{10}) i_f \sin\theta \qquad (17)$$

$$i_f = (-\lambda_{as2} + (a_{12}i_{qs} + a_{13}i_{qr})\cos\theta + (a_{12}i_{ds} + a_{13}i_{dr})\sin\theta)/a_{11} \qquad (18)$$

The constant coefficients of the above equations are as follows:

$$a_6 = 1 - \frac{L_m^2}{L_s L_r} \qquad a_7 = \frac{1}{a_6 L_s}$$

$$a_8 = \frac{L_m a_7}{L_r} \qquad a_9 = \frac{1}{a_6 L_r}$$

$$a_{10} = \frac{2}{3}\frac{\mu L_s}{a_0} \qquad a_{11} = \frac{2}{3}\frac{\mu L_m}{a_0}$$

$$a_{12} = \mu L_s \qquad a_{13} = \mu L_m$$

2.2.4 Equation of torque

Finally, the equation of electro-mechanical torque modifies as follows:

$$T_e = \frac{3}{2}\frac{p}{2}L_m(i_{qs}i_{dr} - i_{ds}i_{qr}) + \frac{p}{2}\mu L_m i_f (i_{qr}\sin\theta i_{dr}\cos\theta) \qquad (19)$$

Thus, with the help of above presented mathematical equations, the modeling of induction motor is carried out using MATLAB/SIMULINK software.

3. Simulation

The general block diagram of simulation is presented in the Fig. 2.

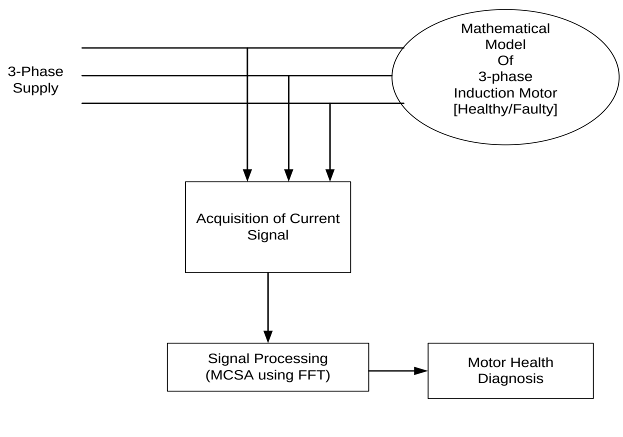

Fig.2 The block diagram of simulation model

The Simulink model is run first in healthy condition and the current data are recorded with the help of

'SimOut' block of Simulink. The model is then run for different levels of stator inter-turn fault namely 3 turns shorted, 5 turns shorted, 7 turns shorted & 10 turns shorted. The models are run for each of the above mentioned conditions at three different loads viz. no load, half load & full load. All the current signals are acquired for each of the cases.

4. Application of FFT

Motor Current Signature Analysis (MCSA) is carried out by doing the FFT analysis of instantaneous values recorded from the simulation. Total numbers of samples collected are 50,000 with 20 μsec fixed sample time i.e. sampling frequency of 50 kHz. Also, as the motor goes under transient in starting, hence initial values are neglected. For the FFT analysis, last 10,000 samples are used. The FFT analysis is performed by writing a MATLAB program. For each of the various conditions, the 10,000 samples of instantaneous values are imported into workspace in a specified variable. The MATLAB code is then run using the imported data to perform FFT of current signal.

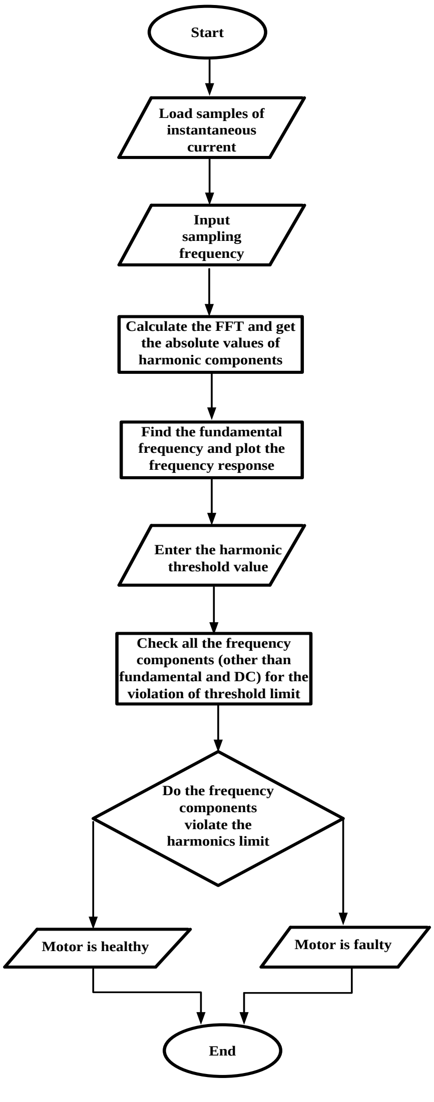

Fig. 3 Flowchart of discrimination program

This program is used to discriminate between healthy and faulty conditions. The flow chart of MATLAB code, which discriminates between healthy and faulty motor, is shown in Fig. 3.

Fig. 4 & Fig. 5 show the current waveform and its frequency spectrum for a healthy motor at full load condition, respectively.

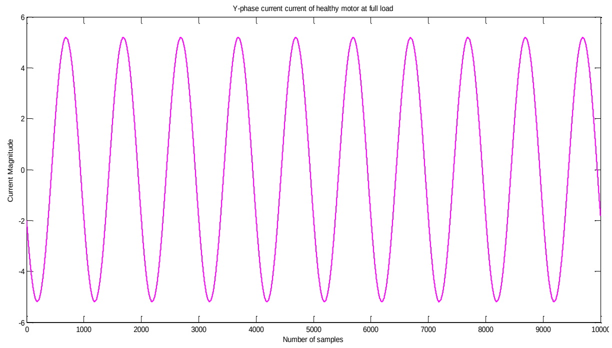

Fig. 4 Current waveform of healthy motor

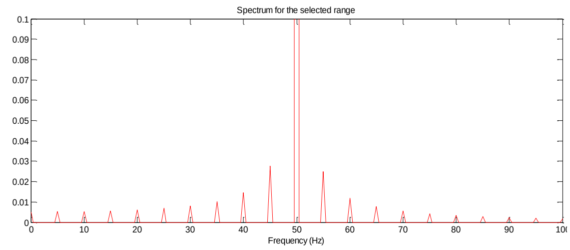

Fig. 5 Frequency spectrum of healthy motor current

5. Results & Discussion

The FFT results are analyzed by plotting the most dominant harmonic components for different conditions of motor i.e. healthy condition and shorted (3 turns, 5 turns, 7 turns & 10 turns) conditions. The figure below presents the plot of most dominating harmonic components of healthy and faulty conditions at full load.

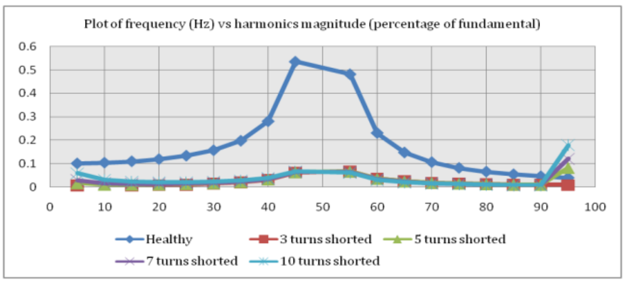

Fig. 6 Plot of most dominating harmonics

It has been observed that in the situation of stator fault, a significant magnitude DC component is introduced in the frequency spectrum of current. While plotting these components, the DC and fundamental components are skipped in order to have clear discrimination. As the DC and fundamental components have very high magnitudes compared to other frequencies, hence plotting them together almost hides other components.

The above graph is plotted between frequency and the magnitudes of harmonics components (taken as percentage of fundamental component magnitude). The harmonic components are obtained from the result of FFT analysis. These harmonic components are first sorted by the magnitude, for different conditions of motor and then they are plotted against a common base of frequency ranging from 0 to 100 Hz. The figure above shows these plots for different conditions of motor which are healthy, 3 stator turns shorted, 5 stator turns shorted, 7 stator turns shorted & 10 stator turns shorted. From the figure there can be seen the clear distinction among healthy and faulty conditions.

Conclusions

The paper presented a novel method of discriminating the health condition of motor with the help of plots of most dominating frequency components present in the stator current. The comparative plotting of these frequency components shows a distinction among different conditions of motor health. The method is simple and has base of widely accepted FFT technique of Motor Current Signature Analysis.

It is seen that the presented method is successful in discriminating between the healthy and faulty conditions of motor reliably & is simple to use.

References

E. T. Esfahani, Wang Shaocheng & V. Sundararajan, (2014), Multisensor Wireless System for Eccentricity and Bearing Fault Detection in Induction Motors, *IEEE/ASME Transactions on Mechatronics*, 19, pp. 818-826.

F. Filippetti, A. Bellini & G. Capolino, (2013), Condition Monitoring and Diagnosis of Rotor Faults in Induction Machines: State of Art and Future Perspective, *IEEE Workshop on Electrical Machines Design Control and Diagnosis*, pp. 196 - 209.

Peter Tanver, Li Ran, Jim Penman & Howard Sedding, (2008), Condition Monitoring of Rotating Electrical Machines, *Institute of Engineering & Technology, London*.

G. Didier, E. Ternisien, O. Caspary & H. Razik, (2006), Fault Detection of Broken Rotor Bars in Induction Motor using a Global Fault Index, *IEEE Transactions on Industrial Applications*, 42, pp. 79-88.

H. Douglas, P. Pillay & A. Ziarani, (2005), Broken Rotor Bar Detection in Induction Machines with Transient Operating Speeds, *IEEE Transaction on Energy Conversion*, 20, pp. 135-141.

Xianghui Huang, T. G. Habetler & R. G. Harley, (2007), Detection of Rotor Eccentricity Faults in a Closed-Loop Drive-Connected Induction Motor using an Artificial Neural Network, *IEEE Transactions on Power Electronics*, 22, pp. 1552- 1559.

P. C. Krause, O. Wasynczuk, S. D. Sudhoff, (2013), Analysis of Electric Machinery and Drive Systems, *IEEE press, Wiley Student Edition*.

R. M. Tallam, T. G. Habetler & R.G. Harley, (2002), Transient Model for Induction Machines with Stator Winding Turn Faults, *IEEE Transactions on Industry Applications*, 38, pp. 632 – 637.

W.T. Thomson & M. Fenger, (2001), Current Signature Analysis to Detect Induction Motor Faults, *IEEE Industry Applications Magazine*, 7, pp. 26 - 34.

A. Gandhi, T. Corrigan & L. Parsa, (2011), Recent Advances in Modeling and Online Detection of Stator Interturn Faults in Electrical Motors, *IEEE Transactions on Industrial Electronics*, 58, pp. 1564- 1575.

M. Dlamini, P. S. Barendse & A. Khan, (2013), Autonomous Detection of Interturn Stator Faults in Induction Motors, *IEEE International Conference on Industrial Technology*, pp. 1700 – 1705.