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Rotor Fault Detection and Diagnosis of Induction Motor using Fuzzy Logic

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Abstract

In the present scenario, online parameter monitoring of induction motors with the help of fault detection algorithms are very useful for the early detection of fault and to protect the motor from catastrophic damages. Rotor of the induction motor is subjected to very low voltages and much higher temperature, compared to the stator winding. Therefore most common failure mode in the rotor of the squirrel cage induction motor is open or broken bar of the rotor. The objective of this paper is to study the effects of rotor fault. It is also proposed to formulate fuzzy inference algorithms for detecting the rotor fault and analyzing their severity. The model of a three phase squirrel cage induction motor developed in RMxprt of MAXWELL software, under healthy condition is taken as the reference for fault detection and analysis. Two dimensional finite element methods are used to analyse the performance of the motor under rotor broken bar fault condition. In this work, fuzzy logic inference algorithms are used to formulate decisions about the motor condition with high degree of accuracy.

Key words

Induction motor, Rotor fault detection, Modeling, Diagnosis, FEM, Stator current amplitude, Fault detection and diagnosis, Rotor broken bar.

1. Introduction

Reliable operation of electrical machine provides energy efficiency and financial benefit to the industry. Faults that may affect the smooth operation of the machine are therefore crucial for the safety which paid special attention of investigators in this area. Parameter monitoring of the machine is important in industry to detect and diagnose the type of fault at an earlier stage. For the past 25 years, substantial research has been carried out for the formulation of new condition monitoring techniques for induction motor drives. M. Sudha and P. Anbalagan (2009), V. P. Mini and S. Ushakumari (2011) explains that the induction motor performance is affected by three types of faults such as electrical faults, mechanical faults and environmentally related faults. The rotor fault detection of three phase squirrel cage induction motor by using an on–line observer is given by Hugo Rodriguez-corties *et al.* in 2004.

Finite Element analysis of rotor broken bar fault of three phase induction motors is given by A. Bentounsi and A. Nicolas (1998). This paper discusses the torque developed in the machine is reduced due to the rotor broken bar fault. With the help of spectral analysis, they had proved that when a rotor bar is broken, normal flux density in the teeth located in front of the defective bar is increased and that of the other side is decreased. A. Bentounsi and A. Nicolas in 1998 proposed a local approach to tackle the problem of breaking bars and end-rings of squirrel cage in induction machines mainly based on the signature of the local variable, like normal flux density. The Vienna Monitoring Method for detection of rotor bar fault of a three phase squirrel cage induction motor is given by Christian Kral and Rudolf S, *et al.* in 2000. The Vienna Monitoring Method compares online voltage model output with a current model and observed the deviations in a rotor fixed reference frame. Szabó Loránd and Dobai Jenő Barna *et al.,* in 2004 explained the current signature analysis for rotor broken bar fault of three phase squirrel cage induction motor. As per this paper, decibel (dB) versus frequency spectrum is used as the current signature pattern to detect the rotor broken bar fault. The Extended Park's Vector Approach (EPVA) for broken rotor bar fault detection of a three phase squirrel cage induction motor is given by Zexiang Ca and Aiyun Gao *et al*., in 2004. Motor Current Signature analysis for rotor fault of an induction motor is given by Carlo Concerti and Giovanni Franceschini in 2008. The features of stator currents and of radial and axial core vibration signals used for the detection and stray flux signals are taken into account to increase the reliability of the diagnostic system. The Artificial Neural Network (ANN) algorithm for broken bar fault detection of three phase squirrel cage induction motor is given by Hayri Arabaci and Osman Bilgin in 2009. According to EPVA, the spectrum of steady stator Current Park's vector module consists of double frequency components.

This paper proposes a fuzzy logic algorithm for detection and diagnosis of rotor broken bar fault of a three phase squirrel cage induction motor, based on the amplitude of stator currents, speed, negative sequence current and peak magnitude of FFT of line currents. It is a realistic and straight forward method to simulate rotor broken bar faults of a three phase squirrel cage induction motor. One fuzzy logic algorithm is proposed for identifying the rotor broken bar fault and analyzing its severity. The detection and analysis of rotor broken bar fault, carried out in this paper is divided into three sections. The first section consists of the complete design of three phase squirrel cage induction motor and develops a machine based on designed values using Rmxprt of the Maxwell Software. The Maxwell 2D analysis of normal machine is included in the second part. The introduction of partial and complete rotor broken bar faults into the healthy machine and the detection and analysis of such fault conditions using fuzzy logic algorithm is discussed in the last section.

2. Causes and effects of rotor faults

The classification of squirrel cage induction motors based on rotor construction is given by Subhasis Nandi and Hamid A. Toliyet in 1999 and V. P. Mini and S. Ushakumari in 2012. In this paper, squirrel cage induction motors are classified into two groups such as cast rotors and fabricated rotors. Cast rotors are commonly used in small machines and fabricated rotors are used in large machines and special applications. The rotor of a squirrel cage induction motor is a cylindrical cage, comprised of axial bars terminated in annular rings. Cast Aluminum is used for the bars and the end rings. The conductors are generally skewed along the rotor length to reduce the noise and torque fluctuations. The thin laminations reduce eddy current losses. The manufacturing defects such as weak joints at the bar ends, internal constraints (electromagnetic and thermal) and external constraints (overload and frequent start-ups) due to wear phenomenon are the main causes of rotor fault in a three phase squirrel cage induction motor. The other reasons for the rotor fault of an induction motor are thermal stresses produced due to thermal overload and unbalance, mechanical stresses produced due to lose laminations and bearing failure, magnetic stresses caused by electromagnetic forces and electromagnetic noise, dynamic stresses arising from shaft torque and centrifugal forces and residual stresses due to manufacturing problem and vibration etc. The rotor is subjected to much lower voltages and much higher temperature compared to the stator windings. Therefore, the most common failure mode in rotors is open or broken rotor bar. Rotor faults are very important because, their symptoms are sensed by usual measurement systems and it will affect the motor movement characteristics. The effects of the rotor fault of an induction motor are fluctuation and reduction in speed and torque, temperature rise due to increase in stator current and harmonic losses.

3. Rotor Fault Detection Methods

This section presents different types of fault detection method that had been proposed to identify the rotor faults of a three phase squirrel cage induction motor. The most frequently used detection methods are Motor Current Signature Analysis (MCSA), Acoustic noise measurement techniques, Artificial Intelligence and Neural network based techniques, Noise and Vibration monitoring techniques, Electromagnetic field monitoring technique using search coils, or coils wound around motor shafts (axial flux related detection), Temperature measurement techniques, Infrared recognition technique, Radio Frequency (RF) emissions monitoring techniques and Chemical analysis, etc.

Online monitoring scheme to detect the rotor broken bar fault of a drive system is given by Hugo Rodriguez-Cortes *et al.* in 2004, based on the spectrum analysis of stator current. The requirement of mathematical model of the machine is one of the drawbacks of this technique. Jarmo Lehtonen *et al.* (2005) explained the fault diagnosis of induction motor with dynamic neural network. In dynamic neural network technique, neural network time-series models are created for the normal and faulty motor and a Bayesian classifier is used to determine the correct classification of the motor condition. The motor current signature analysis of rotor fault detection for a three phase squirrel cage induction motor is given by Aderiano M. Da Silva and Richard J. Povinelli *et.al* in 2006. This method is based on the analysis of three phase stator current envelopes of induction machines using reconstructed phase space transforms. In their paper, signatures of each type of fault from the corresponding three phase current envelope are created. Rotor fault detection analysis of an induction motor using vibration monitoring is given by Carlo Concari, *et.al.* in 2008. Vibrations produced in the core due to inter bar currents of faulty rotor are sensed with the help vibration sensor. This diagnostic system investigates the axial core vibration signals, stator currents and stray flux signals for fault identification.

In almost all of the above methods, the fault detection and analysis of three phase squirrel cage induction motor is performed with the help of mathematical model. The mathematical model of squirrel cage induction motor with rotor broken bar fault is very complex due to the large number of differential equations. The aim of this paper is to detect the effect of partially and completely rotor broken bar fault of a three phase squirrel cage induction motor using Finite Element Method and also to propose a fuzzy logic algorithm for identification and analysis of rotor broken bar fault.

4. Finite Element Method (FEM)

The fault of three phase squirrel cage induction machines can be studied through the physical experiment and computer simulation. The computer simulation is more economical and flexible. Without hardware prototyping, it is easy to change parameters to run the machine at different conditions. The most important part of the computer simulation of rotor fault analysis of induction motor is the modeling of the machine. The induction machine can be modeled using analytical approach or time step finite element method (FEM). Analytical approach is a circuit oriented approach and use linearized parameters for representing the magnetic property of the machine. The time step FEM is more accurate than the analytical approach because it is based on the machine geometry. So the finite element model of an induction motor is suitable for the analysis of rotor fault condition because it studies the behavior of electromagnetic field inside the machine directly based on its geometry and material properties.

Finite Element Method (FEM) is a numerical method for solving a differential or integral equation. It is applied to a number of physical problems, where the governing differential equations are available. The finite element method consists of piecewise continuous function for the solution so that error in the solution is reduced. The performance evaluation of three phase squirrel cage induction machine based on finite element method is given by Ali Ebadi, Mohammad Mirzaie *et al.* in 2011. Rotor fault analysis of three phase squirrel cage induction machine using FEM is given by Mini.V. P. and S. Ushakumari in 2012. This powerful design tool has significantly improved both, the standard of engineering designs and the methodology of the design process in many industrial applications. Some benefits of FEM are increased accuracy, enhanced design and better insight into critical design parameters, virtual prototyping, fewer hardware prototypes, a faster and less expensive design cycle, increased productivity and increased revenue. Basic theory of conventional FEM and direct FEM is given by P Lombard *et al.* in 1992 . Eddy currents, external sources and impedances are the main parameters that depend on the machine performance. In conventional FEM, the differential equations that govern the machine performance is converted into the field variables for analysis. When using conventional FEM, it is difficult to obtain the machine performance taking into account the eddy current, external sources and impedances. In order to overcome this difficulty, direct FEM is used in which, magnetic field circuit is directly coupled to electrical circuit for analysis. So all variables are assumed to vary sinusoidal with time and also two dimensional domains are considered for the analysis. Here, the formulation is implemented in Maxwell 2D software. Maxwell includes 3-D/2-D magnetic transient, AC electromagnetic, magneto static, electrostatic, DC conduction and electric transient solvers that accurately solve for field parameters including force, torque, capacitance, inductance, resistance and impedance.

5. Design of Three Phase Induction Motor

Design of an electric machine is the physical realization of the theoretical concept of the electrical machine to perform the specified task with economy and efficiency. The output equation in terms of fundamental values is converted into the output equation in terms of machine dimensions is the first step of the machine design. The size and shape of the machine depends on its rating. The detailed design of a 3.7 kW, 400 V, 3 phase, and 50 Hz squirrel cage induction motor is given by V. P. Mini and S. Ushakumari (2012). The design of three phase squirrel cage induction motor consists of three parts. The first part consists of the design of main dimensions, the stator and rotor design are included in the second and third part respectively.

5. a. Design of Main Dimension

The stator core diameter of the induction motor ‘D’ and stator core length ‘L’ of an induction motor are known as the main dimensions of a three phase induction machine. The starting point in the design of rotating electrical machines is the selection of specific magnetic loading and specific electric loading. Total flux around the stator periphery at the air gap is called total magnetic loading (Pφ). The total number of ampere conductors around the armature periphery is called total electric loading (I_zZ).

The specific magnetic loading is the average flux density (B_{avg}) over the air gap of the machine and the specific electric loading (*ac*) is the number of stator ampere conductors per meter of stator periphery at the air gap. The factors considered for the selection of average flux density are power factor, iron loss and over load capacity. The value of flux density in the air gap should be small, otherwise the machine will draw a large magnetizing current and the power factor is very low. The increased value of gap density results in increased iron loss and decreased efficiency. For a large value of air gap flux density, the flux per pole is large and the leakage reactance becomes small. With small leakage reactance, the machine has large over load capacity. Most of the induction machines have an over load capacity of twice the horse power but the speed is reduced. There is a trade-off between the two, for a 50 Hz machine of normal design, the value of B_{avg} lies between 0.3 and 0.6 wb/m ^{2} and the specific electric loading (*ac*) value corresponding to B_{avg} (0.45 wb/m^2) is 26000.

The value of efficiency and power factor of an induction machine for a 50 Hz machine is selected from the table. Efficiency η = 0.83 and power factor pf = 0.84. The kVA rating of an induction machine in terms of fundamental values and machine dimensions are expressed in eqn (1) and eqn (2). That is,

$$Q = \frac{kW}{\eta \times pf} \tag{1}$$

$$Q = C_0 D^2 L n s \tag{2}$$

Where C_0 is the output coefficient

$$C_0 = 11\, B_{avg} ac K_w \times 10^{-3} \tag{3}$$

$$D^2 L = \frac{Q}{C_0 n_s} \tag{4}$$

The product D^2L is obtained from (4). The ratio of core length (L) to pole pitch (τ) is used for the separation of stator core diameter and stator core length of an induction machine. For economic and good efficiency induction machine, the ratio of (L/τ) is taken as 1.5. The values of stator core length (L) and stator core diameter (D) is obtained as ;

$$D = 0.118\text{m}, \quad L = 0.139\text{m}, \quad \tau = 0.09263$$

The core length of the designed machine is higher than 100 mm and therefore ventilating ducts are provided. The width of each duct is 10 mm. So the Net iron length of the machine,

$$L_i = 0.9\left(\mathrm{L} - 0.01\right) = 0.1161\mathrm{m} \quad (5)$$

5. b. Stator Design

Important points included in the stator design are the determination of stator turns per phase, stator conductors per slot, stator slot dimension and stator core dimension and conductor size.

The stator turns per phase

$$T_s = \frac{\mathrm{E_s}}{4.44\ \mathrm{f}\ \phi_\mathrm{m} k_w} = 325 \quad (6)$$

Semi enclosed slots are used for small machines. For a 4 pole 36 slots machine, stator conductors per slot is

$$Z_{ss} = \frac{6\,T_s}{S_s} = 54 \quad (7)$$

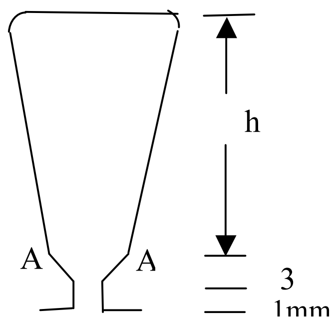


Fig. 1 Dimensions of the stator slot

The actual number of stator turns per phase T_s = 324 and stator conductors per slot Z_{ss} = 54. Mush winding in tapered semi enclosed slots is used for the stator with coil span $\mathrm{C_s}$ = 9. To determine the conductor size, consider the current density of 4 A/mm^2 and diameter of enameled conductor $d_s = 1.37$ mm

The dimension of the stator slot is shown in fig.1. For determining the dimension of the stator slot, consider the space factor for the slot is 0.4 and lip = 1 mm, wedge = 3 mm and height 'h' = 30 mm, bottom width =11.25 mm and depth dss = 34 mm. So length of mean turn L_{mls} is

$$L_{mls} = 2\mathrm{L} + 2.3\tau + 0.24 = 0.731\mathrm{mm} \quad (8)$$

The outside diameter of stator core D_o is

$$D_o = D + 2d_{ss} + 2d_{cs} = 228 \text{ mm} \quad (9)$$

where d_{cs} is the depth of the stator core

5. c. Rotor Design

The selection of number of rotor slots in squirrel cage induction motor is very important. With certain combination of stator and rotor slots, the machine may refuse to start or may crawl at synchronous speed. In some cases, severe vibrations may occur and generating excessive noise.

These effects are produced by harmonic fields. The harmonic fields are responsible for increase in stray load losses and increased motor heating.

As per rules for selecting the number of rotor slots of a three phase induction motor [20], the number of rotor slots S_r is 26 ;

The rotor diameter

$$D_r = D - 2l_g = 117.2 \text{ mm} \tag{10}$$

Where l_g is the length of air gap and it is 0.4 mm The rotor slot and bar dimensions of the three phase squirrel cage induction motor depends upon the rotor bar current I_b.

$$I_b = \frac{2\, m_s\, k_w\, T_s}{S_r} I_s \cos\phi \tag{11}$$

where 'm_s' is the number of stator phases, 'k_w' is the winding factor and 'T_s' is turns per phase in the stator. Important rotor dimensions are given in table.1

Table.1 Important rotor dimensions of 3.7 kW 3-φ squirrel cage induction motor

Rotor part of three phase induction motor	Dimensions
Width of the rotor slot, W_{sr}	6.8 mm
Depth of the rotor slot, d_{sr}	10.3 mm
Rotor bar conductor dimensions	6.5 X 8.0 mm^2
End ring dimensions	8.5 x 11 mm
End ring depth d_e	11 mm
End ring thickness t_e	8.5 mm
End ring outer diameter D_e	96.6 mm
End ring Inner diameter	74.6 mm

6. Fuzzy logic based diagnosis approach

Fuzzy logic is known as a multi-valued logic derived from fuzzy sets for approximate reasoning. The application of fuzzy logic system in condition monitoring of electrical machines is given by Lasurt. *et al.* (2000), M. E. H. Benbouzid *et al.* (2001) and V. P. Mini *et al.* (2012). During the fault diagnosis, there are situations where the fault may fall into some range which cannot be categorized as "good" or "bad" perse. Since fuzzy logic mimics human thinking, it can be used for fault diagnosis from vague information. A diagnostic technique can be developed by integrating human knowledge and experience with fuzzy sets and fuzzy rules (which are obtained from the amplitude features of the input variables). These fuzzy rules and fuzzy sets which help in the formulation of the knowledge database on the basis for fuzzy inference, the induction motor condition can then be diagnosed using a compositional rule of fuzzy inference. This fuzzy inference system comprises the fuzzy system input variables, output variables and linguistic variables. A summary is given in the following sections.

6. a. Fuzzy system input-output variables

The stator currents, negative sequence current, speed and FFT of the stator currents are taken as the input variables for condition monitoring algorithm. The induction motor condition can be deduced by observing the amplitude of stator currents, negative sequence current, speed and magnitude of FFT of the stator currents of the machine under different fault conditions. Interpretation of results, directly from the input variables is very difficult, because the input amplitudes are vague. Therefore, fuzzy logic is used to represent numerical data as linguistic information. In this work, the fuzzy logic algorithm is used for rotor broken bar fault detection and for analysing the severity of fault. For this case, six variables such as each phase RMS amplitude of stator current *Ia, Ib* and *Ic* , amplitude of negative sequence current I_{neg}, amplitude of speed and magnitude of FFT of the stator currents are used as the input variables. The motor condition, '*MC'*, is chosen as the output variable. All the system inputs and outputs are defined using fuzzy set theory.

6. b. Linguistic Variables

It is known that basic tools of fuzzy logic are linguistic variables. Their values are words or sentences in a natural or artificial language, providing a meaningful systematic manipulation of vague and imprecise concepts. For rotor broken bar fault analysis, the output is the term set T(MC), interpreting motor condition, '*MC'*, as a linguistic variable, could be *T(MC) = {Normal (NR) , Slightly faulty (SLF), Medium faulty (MF) ,Seriously Faulty (SEF)}*. The input variables, *Ia, Ib*, and *Ic* are interpreted as linguistic variables, with term set *T(Q) = {Very Very Low(VVL), Very Low (VL),* Low (L), *Medium(M), High(H),Very High (VH), Very Very High (VVH)},* the negative sequence current amplitude I_{neg} is interpreted as linguistic variables with term set $T(I_{neg})$ *= {Very Very Very Small (VVVS), Very Very Small (VVS), Very Small* (VS), S*mall (S), Medium (M), Large(L), Very Large (VL), Very Very Large (VVL)}, S*peed amplitude *N* is interpreted as linguistic variables, with term set *T(N)= {Very Very Very Small (VVVS), Very Very Small (VVS), Very Small (VS), Small (S), Medium (M), Large (L), Very Large (VL) Very Very Large (VVL), Very Very Very Large(VVVL)}* and magnitude of FFT is interpreted as linguistic variable with term set *T(/FFT/*)= *{Small Small Small (SSS), Small Small(SS), Small(S), medium(M), Large(L), Large Large (LL),Large Large Large(LLL)}*

where $Q = I_a, I_b, I_c$ respectively.

6.c. Fuzzy membership functions

In order to handle the fuzzy data, it is necessary to convert the actual data into the fuzzy data based on certain membership functions. In this work, trapezoidal functions are used as the membership functions.

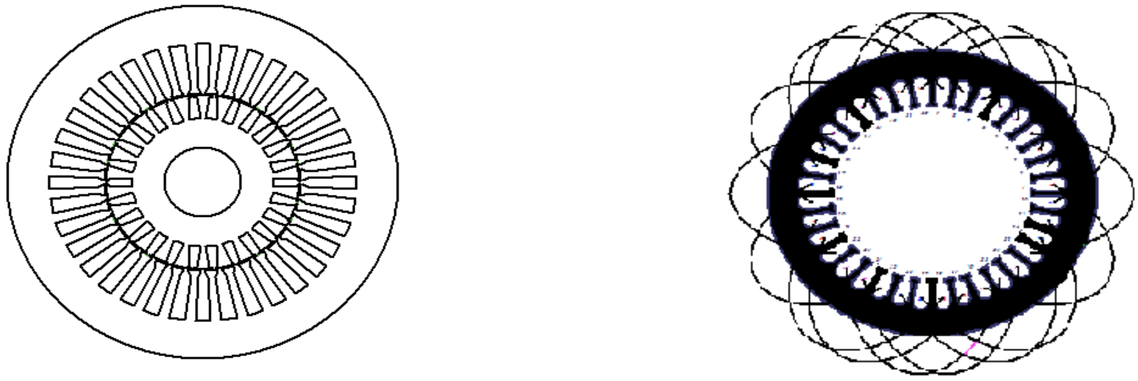
Table 2. Fuzzy output membership function value ranges and corresponding motor condition for rotor broken bar faults

Output membership value range	Motor condition
0.0 – 3.0	Normal *(NR)*
2.5 – 5.5	Slightly Faulty *(SLF)*
5.0 – 8.0	Medium Faulty *(MF)*
7.5-10.5	Seriously Faulty *(SEF)*

Fuzzy rules and membership functions are constructed by observing the data set. For the measurements related to the stator currents, more insight into the data is needed, so membership functions will be generated for all input and output variables. According to the severity of the fault, fault condition is divided into four fuzzy sets. The output fuzzy linguistic variables and their membership function value ranges for rotor broken bar fault are given in table 2. For detection and diagnosis of faults, the stator currents, negative sequence component of stator current, speed and magnitude of FFT are converted into corresponding fuzzy value as inputs. The outputs are then evaluated by fuzzy logic inference engine using the knowledge base.

7.0 Development of 3-ϕ IM Using RMxprt

A fuzzy logic algorithm is developed for the detection and diagnosis of the rotor broken bar fault of a three phase squirrel cage induction motor. In this work, a 3.7 kW, 400 V, 3 phase, 4 pole, 50 Hz; squirrel cage induction motor is used for the simulation. The three phase squirrel cage induction machine used for simulation is developed in RMxprt of Maxwell software using design data. The complete model of a three phase induction motor and its stator winding developed by Rmxprt of Maxwell software is shown in fig 1.a. and 1.b respectively.



a. b.

Fig. 1 a. Complete model of three phase squirrel cage induction motor. b. stator winding

Using classical analytical motor theory and equivalent magnetic circuit methods, RMxprt can calculate the machine performances, make initial sizing decisions, and perform hundreds of what-if analyses within seconds. The performance characteristics of designed three phase squirrel cage induction motor are shown in fig. 2.

Fig. 2 Performance characteristics of designed three phase squirrel cage induction motor

Fig.2 shows the variation of efficiency and power factor with output power respectively, the efficiency of the three phase induction motor depends upon the constant losses and variable losses, variable loss is directly proportional to the square of the load. So the efficiency of three phase induction motor reaches a maximum level at a particular load condition, then efficiency decreases with increase in load. The power factor curve shows that three phase induction motor has very low power factor at no load, which increases to a certain maximum value and begins to reduce. The variation of torque with speed is shown in fig. 3, it shows that like efficiency, the torque also increases initially and then reduces.

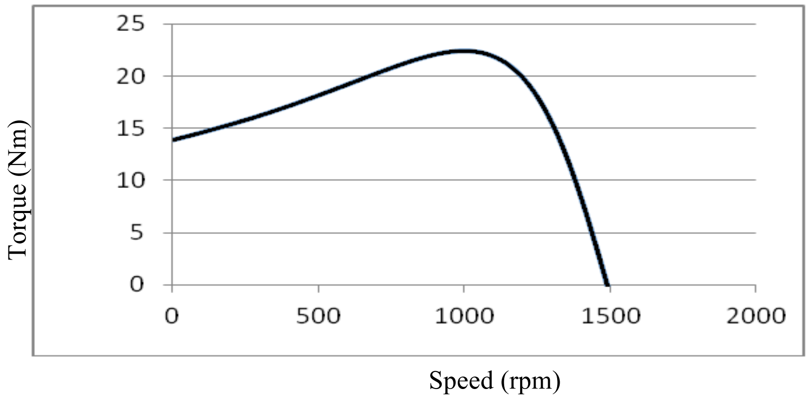


Fig. 3 Speed – Torque characteristics of designed three phase squirrel cage induction motor

7.a. Simulation of induction motor by using 2D FEM

After performance calculations obtained in RMxprt, the machine developed in RMxprt is exported to the Maxwell 2D to set up the complete Maxwell project (2D/3D) including geometry, materials, boundary conditions and excitations with coupling circuit topology for electromagnetic and transient analysis. The Maxwell 2D model of designed three phase squirrel cage induction motor is shown in fig. 4

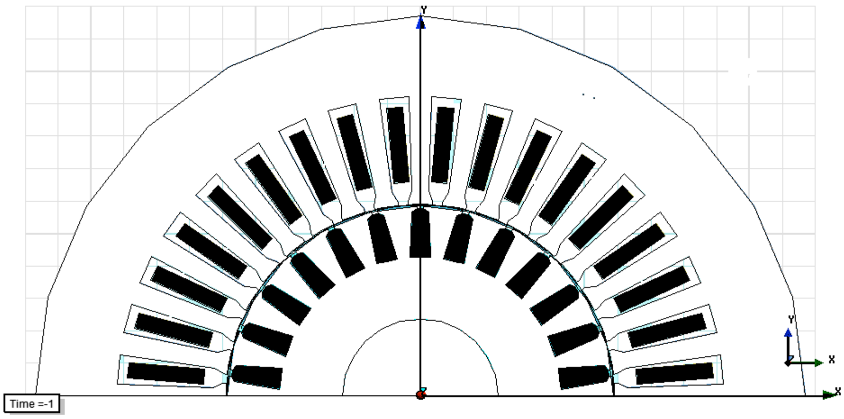


Fig. 4 Maxwell 2D model of three phase induction motor

The electrostatic field simulator of Maxwell 2D, automatically computes the basic field quantities of the machine such as the scalar electric potential, the electric field and the electric flux density from the applied potential. The derived quantities such as forces, torque and energy of the motor can be calculated from the above basic field quantities. Responses of speed and torque of the three phase induction motor under no load condition obtained from the Maxwell 2D simulator is shown in fig. 5.

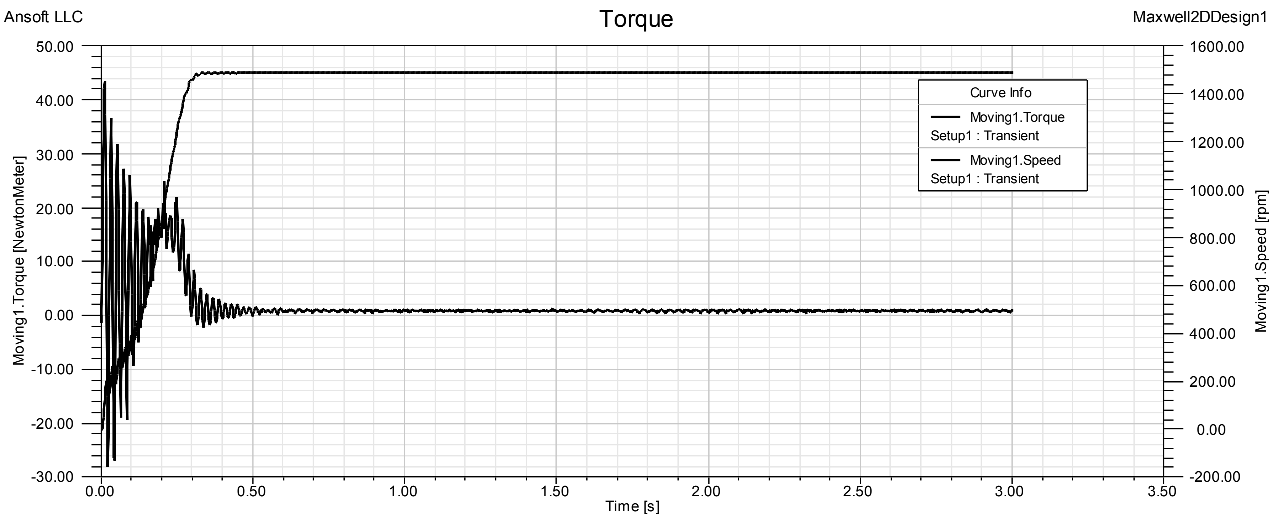


Fig. 5 Speed and torque responses of healthy induction motor on no load

In the normal no load condition, the starting torque is about 44 Nm and the speed is about 1480 rpm and the motor will maintain the constant speed within 0.3 sec. In order to realise the variations of the load, a torque with the following equation has been considered as the load.

$$T_{LOAD} = \left(\frac{T_{FL}}{\omega_{rated}^2} \right) \times \omega^2 \tag{12}$$

Where T_{FL} is full load torque, ω, ω_{rated} are actual speed and rated speed of the machine, respectively.

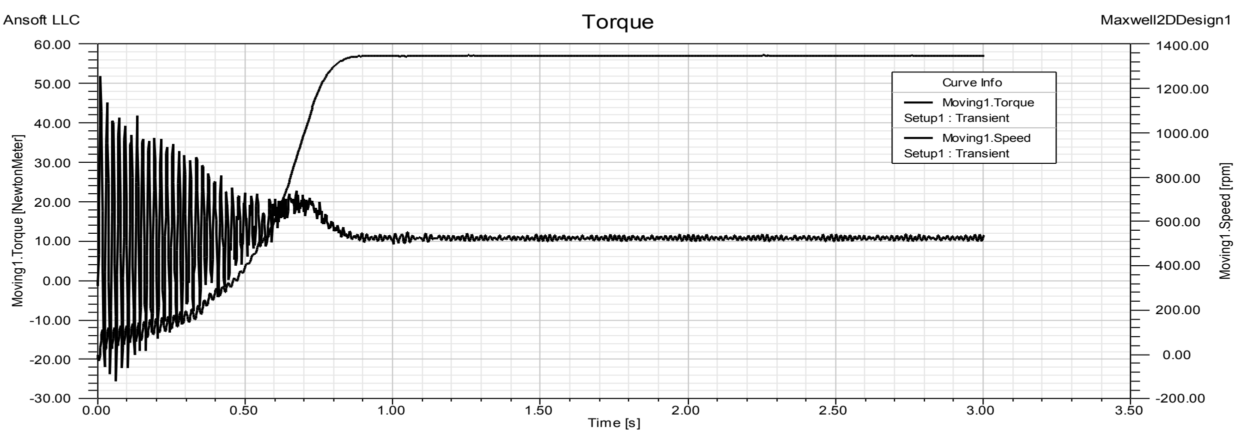


Fig. 6. Speed and torque responses of healthy induction motor on load

The responses of speed and torque of three phase induction motor on loaded condition is shown in fig. 6. If the load is increased, the speed of the motor is decreased and the motor will take more time to attain the steady state speed. For 10 Nm load, the motor speed is reduced to 1380 rpm and the steady state speed is reached after 0.8 seconds only. The starting torque of three phase induction motor is increased due to increasing the load torque. From fig. 5 and 6, it is seen that the starting torque of a healthy machine under no load condition is about 44 Nm and at 10 Nm load condition, the starting torque is increased to 52 Nm.

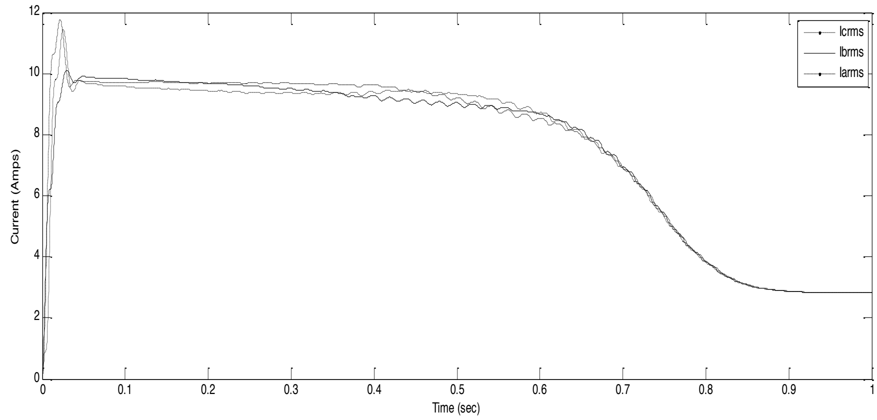


Fig. 7. RMS values of I_a , I_b, I_c on load condition

Fig. 7. shows the RMS values of phase currents of three phase squirrel cage induction motor on 10 Nm loaded condition. The negative sequence current waveform and magnitude of FFT of stator current is shown in fig. 8. The stator current amplitudes, amplitudes of negative sequence current, amplitudes of speed and magnitude of FFT are applied to the fuzzy logic detection algorithm and the corresponding fuzzy rule viewer for healthy condition of the motor is shown in fig. 9. The results are taken during acceleration from standstill to full speed.

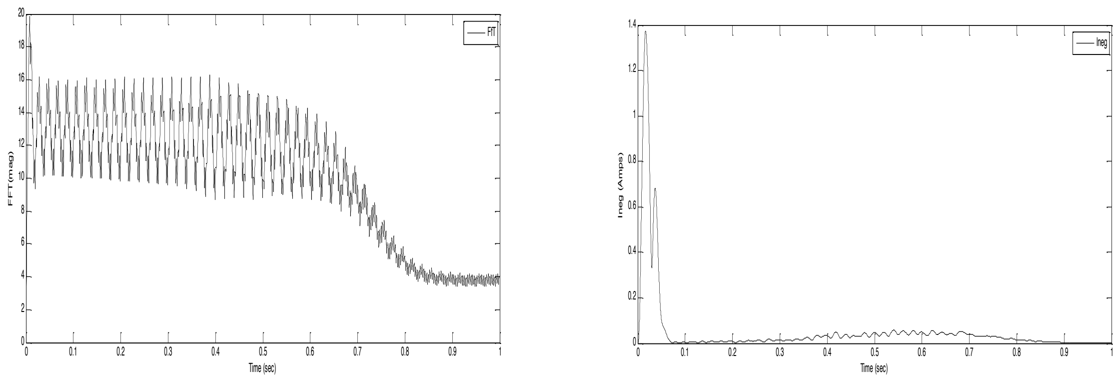


Fig. 8. The negative sequence current and magnitude of FFT under healthy condition

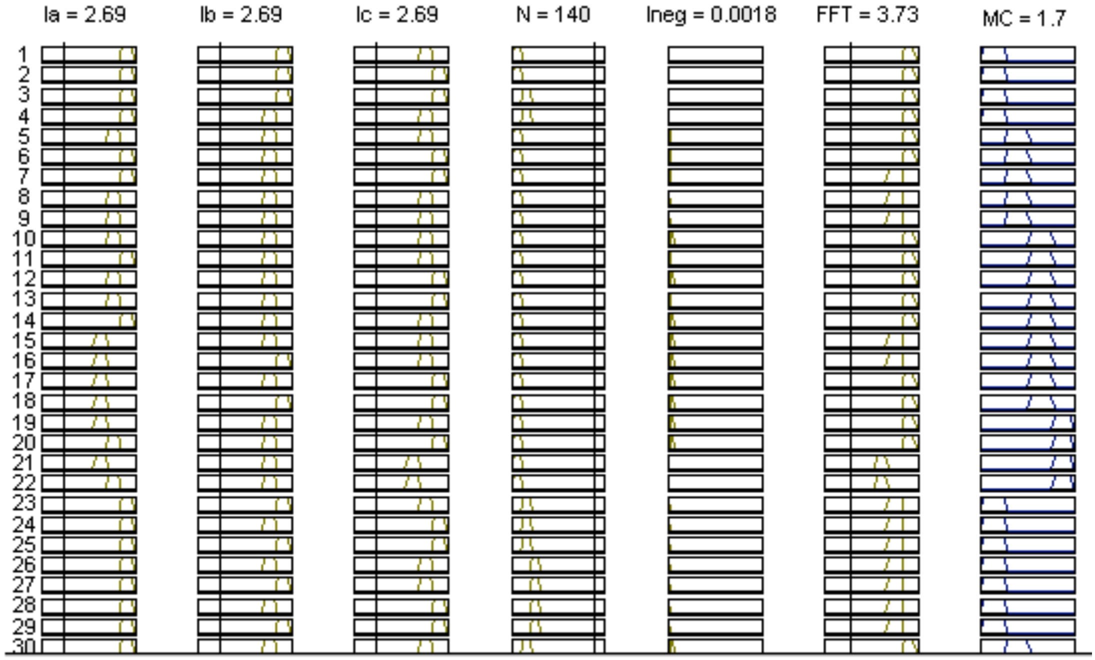


Fig. 9. Fuzzy inference diagram for an induction motor in healthy condition

In fig. 9, RMS values of input current are $I_a = I_b = I_c = 2.69$ A, the magnitude of I_{neg} is 0.0018 A, speed (140 rad/sec) , the magnitude of FFT of stator current is 3.73 and the corresponding output membership function value is 1.7 for healthy condition. For analysing the severity of rotor broken bar fault of a squirrel cage induction motor, each bar of the rotor is partially and fully broken with the help of splt tool of the maxwell 2D software.

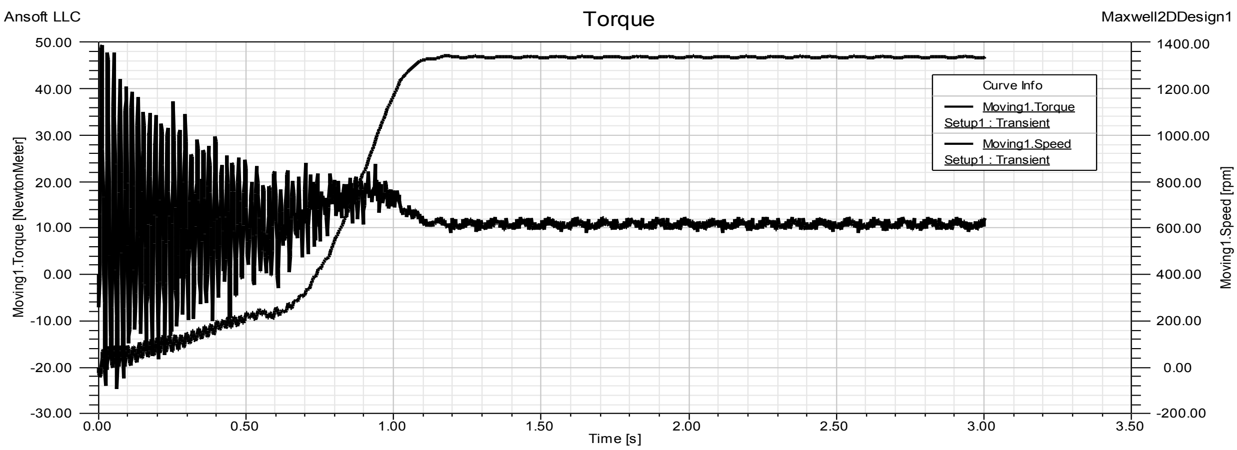


Fig. 10 Speed and torque responses of motor under one bar partially broken

Fig. 10 shows the responses of speed and torque of induction motor when one rotor bar is partially broken and fig. 11 shows the RMS values of phase currents of three phase squirrel cage induction motor under one broken bar fault. Because of the rotor broken bar condition, the torque graph shows more pulsation and takes more time (1.2 sec) to reach a steady state, as compared to the normal running condition. Due to the partially broken bar fault, fluctuations are produced in the speed response and its magnitude is reduced.

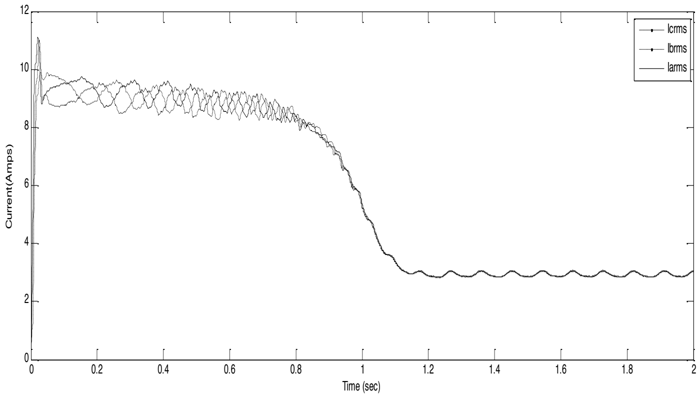


Fig. 11 RMS values of I_a, I_b and I_c when one bar is broken

The magnitude of stator currents are decreased at starting and takes more time (1.2 sec) to reach steady state as compared to the normal running condition. The magnitude of steady state stator currents are increased due to break in rotor bar.

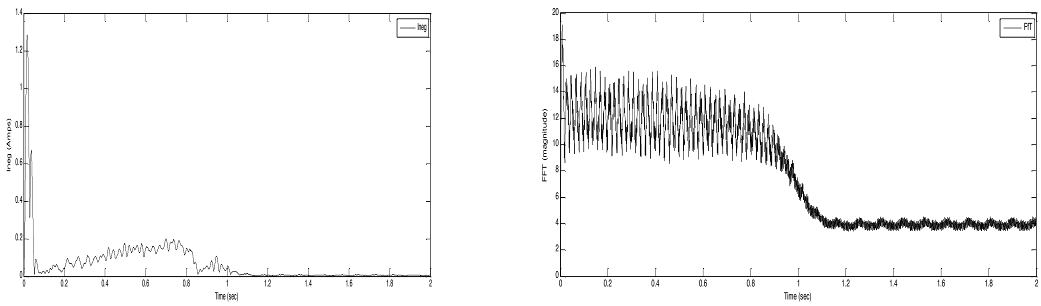


Fig. 12. The negative sequence current and FFT under one broken bar fault

The negative sequence current response and magnitude of FFT under one rotor broken bar fault condition is shown in fig.12. Reduction of starting current and fluctuation in the rms values of currents are the other after effects of rotor broken bar fault in three phase induction motor. Due to the break in rotor bar, the phase current waveforms show more fluctuations due to increase in harmonics. The effect of increase in harmonics is also incorporated into the fault detection algorithm as FFT magnitude. From fig. 8 and 12, it is shown that the FFT magnitude of healthy machine is less than that of faulted condition. The fuzzy inference diagram for slightly fault condition is shown in fig. 13.

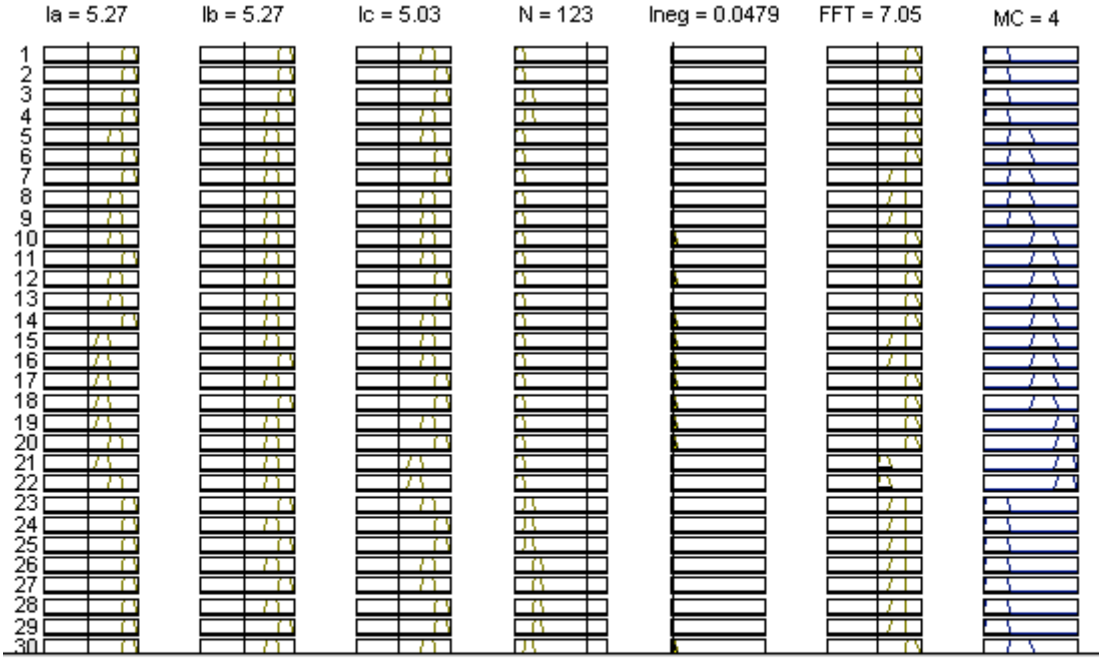


Fig. 13. Fuzzy inference diagram for an induction motor in slightly faulty condition

Fig. 14 shows the speed and torque charectaristics of three phase induction motor under two consecutive rotor broken bar fault condition. Due to increasing severity of the fault, the fluctuations in speed and torque increases and it takes more time to reach the steady state speed.

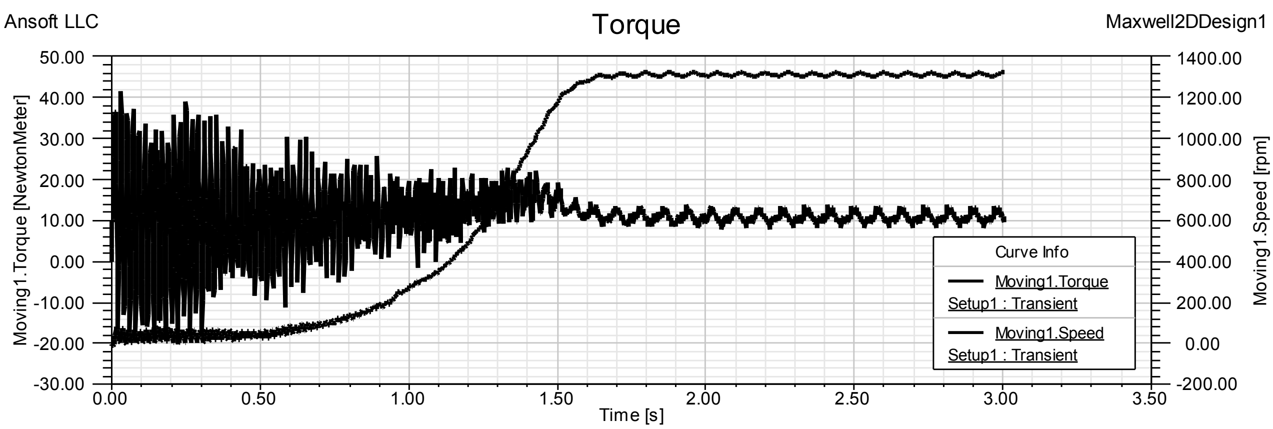


Fig. 14 Speed and torque response of motor under two bar broken

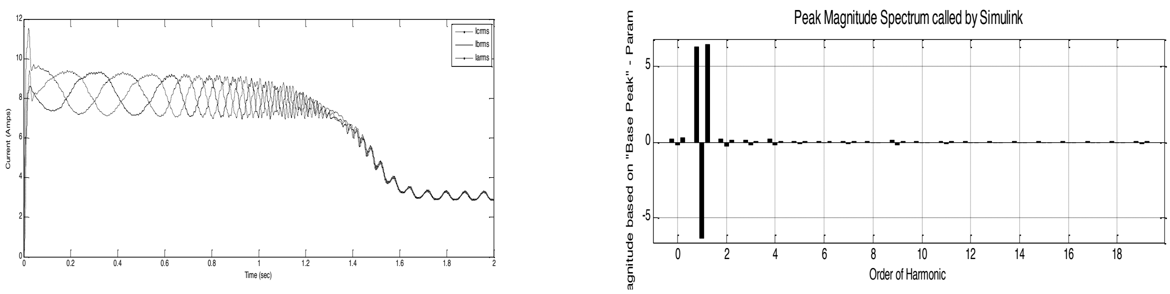


Fig. 15 RMS values of I_a, I_b, I_c and its harmonic chart when two bar broken

Fig.15. shows the variation of RMS values of phase current and its harmonic chart of a three phase induction motor under two consecutive numbers of rotor bar are in broken condition. The harmonic chart is also called peak magnitude spectrum. It indicates the variation of order of harmonics with its peak magnitude. When a broken bar fault is occurred in the machine, the fluctuations of current and thus harmonics is also increased due to increase in severity of the fault. Harmonic chart of three phase induction motor on two consecutive rotor bar broken fault shows that, the harmonic increases with increase in the severity of the fault. The speed and torque responses of a three phase induction motor under three rotor bar broken fault is shown in fig. 16. In this condition, speed did not reach the steady state condition and the torque response has more fluctuations.

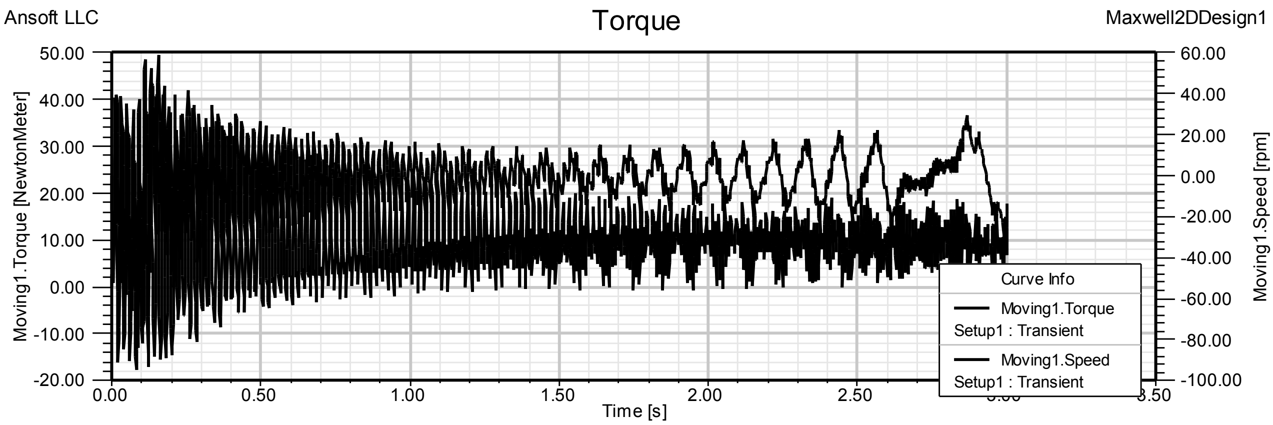


Fig.16 Speed and torque response of motor under three bar broken

The pictorial representation of average torque of a three phase squirrel cage induction motor under different number of broken bar fault condition is shown in fig. 17. It is clear that, the average torque reduced with increase in number of rotor broken bar.

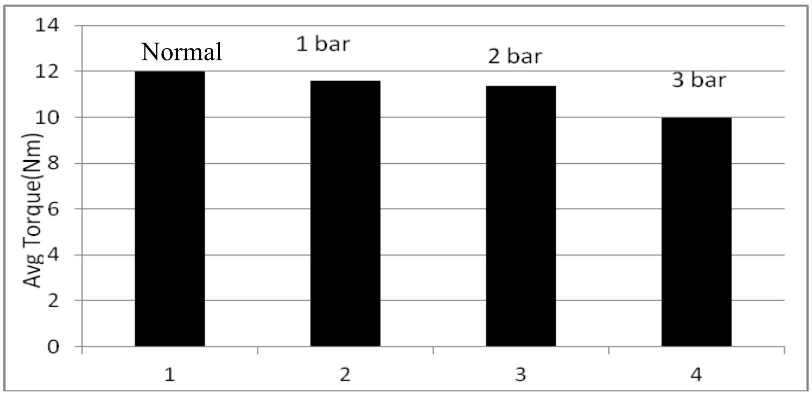


Fig.17 Pictorial representation of average torque for different number of rotor broken bar

Four output fuzzy sets are considered for analyzing the severity of the rotor broken bar fault of a three phase squirrel cage induction motor. These output fuzzy sets are Normal, Slightly faulty, Medium faulty and seriously faulty condition. The magnitudes of all input quantities such as stator current amplitudes, amplitudes of negative sequence current, amplitudes of speed and magnitude of FFT and output fuzzy membership values for all fault fuzzy sets, such as healthy condition, slightly faulty, medium faulty and seriously faulty conditions respectively are given in table 3.

Table 3. Simulated results of Fuzzy detection algorithm for rotor broken bar fault

Inputs						Output	
I_a(A)	I_b(A)	I_c(A)	I neg (A)	N (rad/sec)	FFT	MC	Condition
2.69	2.69	2.69	0.0018	140	3.73	1.7	Normal
5.27	5.27	5.03	0.0479	123	7.05	4	Slightly faulty
7.37	7.17	7.4	0.8	75.8	9.6	6.5	Medium faulty
7.6	8.7	7	0.035	1.2	8.8	8.8	Seriously faulty

The motor condition is decided according to the output membership function value considered in the design of fuzzy logic detection algorithm. The output membership function value ranges are given in table 2 for different types of motor condition.

7. Discussion

The work done in this paper on rotor fault detection and diagnosis of three phase induction motor using fuzzy logic algorithm is accessible to any industry that can install the detection algorithm module in concerned three phase induction motors. The extracted current, speed signals and FFT magnitude of stator currents from the working machine are applied to the fuzzy inference algorithm after processing. This algorithm will indicate the motor condition whether it is healthy or damaged. Additional features are also added to the algorithm for analyzing the severity of the fault. For analyzing the severity of the fault, four fuzzy sets are included in this algorithm. This fuzzy inference algorithm facilitates the early detection of the motor fault, thereby reducing the maintenance cost and protects the machine from the catastrophic faults.

8. Conclusion and future scope

The symmetrical three phase squirrel cage induction motor model is proposed for analyzing rotor faults. No such attempts are reported in the literature, in the context of induction machine protection from the rotor broken bar faults. The squirrel cage induction motor proposed in this work is designed and developed in RMxprt of the Maxwell 2D software. The rotor fault is simulated by exporting the model of three phase induction motor developed using Rmxprt to Maxwell 2D. The severity of the fault is analyzed by varying the number of rotor broken bar. From the harmonic analysis of the machine under different rotor broken bar fault conditions, it can be concluded that the harmonics increases with increase in severity of the fault. With increase in harmonics, the fluctuations in the stator current increases. The thermal stress in the induction motor increases with increase in fluctuations in current, this will worsen the avalanche type damage of rotor. Another effect of rotor fault of a three phase induction motor is the reduction in electromagnetic torque and starting current in the stator phases. Due to these effects, performances of three phase squirrel cage induction motor become poor. So the fault identification device is very important in the general purpose industrial drives that will use the squirrel cage induction motor. A method using fuzzy logic to interpret stator current signals, speed of induction motor and magnitude of FFT for its condition monitoring is also presented. The fuzzy decision system is achieved with high diagnosis accuracy. The proposed method can be extended to identify and analyze the switching fault of an induction motor drive system by using fuzzy inference.

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Appendix A: Motor Parameters

Horse Power: 3.7 kW, Line Voltage: 415 V, No. of Poles: 4, Rated speed: 1500 rpm / 50Hz,

Nomenclature

D	Stator core diameter	*Zss*	Stator Conductors per slot
L	Length of Induction motor	*Cs*	Coil Span
Pφ	Total Magnetic loading	*Do*	Outside diameter of the stator core
Bavg	Specific Magnetic Loading	*Dr*	Rotor Diameter
Ac	Specific Electric Loading	*lg*	Gap length
Kw	Winding Factor	*ms*	Number of Phases
Q	input kVA	*Ss*	Stator Slots
T	Pole Pitch	*Sr*	Rotor Slots
Ts	Stator turns per phase	*dcs*	Stator Core Depth