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FUZZY LOGIC BASED FAULT DETECTION IN INDUCTION MACHINES

Priyanka.D. Pawar*[1] and C. Veeresh[2]
* [1,2]Department of Electrical Engineering SND College Of Engineering , Yeola

ABSTRACT

Three phase induction motors have been utilized in industrial applications, mainly due to their efficiency and reliability. These motors have good properties such as increased stability, robustness, durability, large power to weight ratio, low production costs and controllability easiness. All machines realise various stresses during operational conditions. These stresses might lead to some modes of failures or faults. Condition monitoring is necessary in order to prevent faults. These faults, are necessary to be identified and categorized, as soon as possible as they can end up in serious damages if not detected in due time. Different techniques of fault monitoring for induction motors are broadly classified as techniques based on model, signal processing, and soft computing. For model based techniques, exact models of the faulty machine are required for good fault diagnosis. Sometimes it is difficult to obtain exact models of the machines and also to apply model based techniques.

The aim of this thesis is to present model based fault detection and diagnosis schemes for three phase induction motors relying on the fuzzy logic based induction motor health monitoring approach. The three-phase induction motor model has been developed instead of two phase model (d-q representation), which is very commonly used. This is because the two-phase model is driven under balance operation. The simulation results have been presented motor performance in healthy and faulty cases such as stator currents, torque, speed of the motor, symmetrical components of motor current and health monitoring index. The efficiency of the proposed scheme has been extended evaluated with simulation studies for the cases of a normal operation, turn to turn short in one phase winding, break in stator winding, unbalance in input voltage and one phase fault.
Keywords: *Induction Motor (IM), Fuzzy Logic (FL), Stator Faults, MATLAB.*

I. INTRODUCTION

An induction motor or asynchronous motor is a type of alternating current motor where power is supplied to the rotor by means of electromagnetic induction. The three phase induction motors due to their simple construction, high reliability and low cost, have dominated in the field of electromechanical energy conversion. Modern industrial machines are mutual operation dependent with high cost of unexpected breakdowns. Thus condition monitoring techniques comprising of fault diagnosis and prognosis are of great concern in industry and are gaining increasing attention.

The squirrel-cage induction motor is simpler, more economical, and more rugged than the wound-rotor induction motor. A squirrel-cage induction motor is a constant speed motor when connected to a constant voltage and constant frequency power supply. If the load torque increases, the speed drops by a very small amount. It is therefore suitable for use in constant-speed drive system. On the other hand, many industrial applications require several speeds or a continuously adjustable range of speeds. DC motors are traditionally used in adjustable drive systems. However, since DC motors are expensive, and require frequent maintenance of commutators and brushes. Squirrel-cage induction motors are preferred because they are cheap, rugged, have no commutators and are suitable for high-speed applications. In addition, the availability of solid state controllers has also made possible to use squirrel-cage induction motors in variable speed drive systems. The squirrel-cage induction motor is widely used in both low performance and high performance derives applications because of its roughness and versatility. Electrical machines are extensively used and core of most engineering system. These machines have been in all kinds of industries. An Electrical machine is defined as an asynchronous machine that comprises magnetic circuit which interlinks with two electric circuits, rotating with respect to each other and in which power is transferred from one circuit to the other by electromagnetic induction. It is an electromechanical energy conversion device in which the energy converts from electric to mechanical form. The energy conversion depends upon the existence in nature of phenomena interrelating magnetic and electric fields on the one hand, and mechanical force and motion on the other. The rotor winding in induction motors can be squirrel cage type or wound rotor type.

Electrical machines are frequently exposed to non-ideal or even detrimental operation environments. An electrical machine is defined as an asynchronous machine that comprises magnetic circuit which interlinks with two electric circuits, rotating with respect to each other and in which power is transferred from one circuit to the other by electromagnetic induction. It is an electromechanical energy conversion device in which the energy converts from electric to mechanical form. The energy conversion depends upon the existence in nature of phenomena interrelating magnetic and electric fields on the one hand, and mechanical force and motion on the other. The rotor winding in induction motors can be squirrel cage type or wound rotor type. These circumstances include overload, insufficient lubrication, frequent motor starts / stops, inadequate cooling, etc.

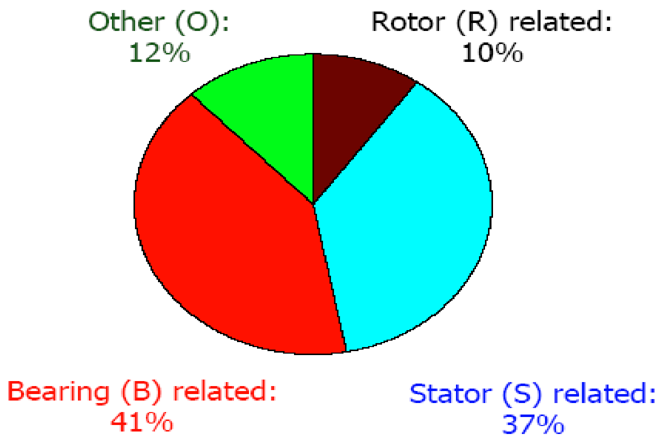

Figure 1: Distribution of induction motor faults

Under these conditions, electrical motors are subjected to undesirable stressed, which put the motors under risk of faults or failures. There is need to improve the reliability of motors due to significant positions in applications. According to IEEE Standards 493-1997, the most common faults and their statistical occurrences are listed in Table 1. This table is based on a survey on various motors in industrial applications. According to the table, most faults happen to bearing and windings. A 1985 statistical study by the Electrical Power Research Institute (EPRI) provides similar results *i.e.*, bearing (41%), stator (37%), rotor (10%) and other (12%).conventional controllers; expert knowledge is used rather than differential equations to analyze a system. A FL based approach can help to diagnose faults in induction motors. FL is like a human thinking process and natural language based decisions to be made based on information. FL allows items to be categorized as having a certain membership degree in a particular set. During fault diagnosis, there are various situations in which an object is not "Good" or "Damaged", but may fall into some interior category. According to the fact that induction motor condition interpretation is a fuzzy concept, here the motor condition is described using linguistic variables. Fuzzy subsets and respective membership functions reflect amplitudes of stator current. A knowledge base, comprising rule base is built to support the fuzzy inference. The condition of induction motor is diagnosed using fuzzy inference rules. The obtained results indicate that the proposed FL approach is capable of highly accurate diagnosis. Humans express knowledge (like an electrical machine referred as "somewhat secure", "little overloaded").This linguistic input can be represented by a fuzzy system.

Faults in Induction Machines

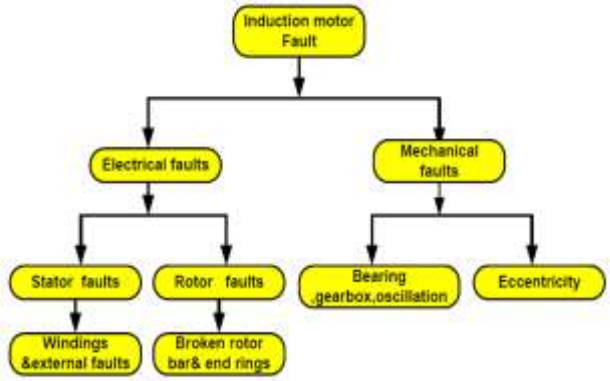

Figure 1: Fault classification in induction motors

Induction machine equations

The figure shows the two dimensional diagram of three-phase IM with stator and rotor windings.

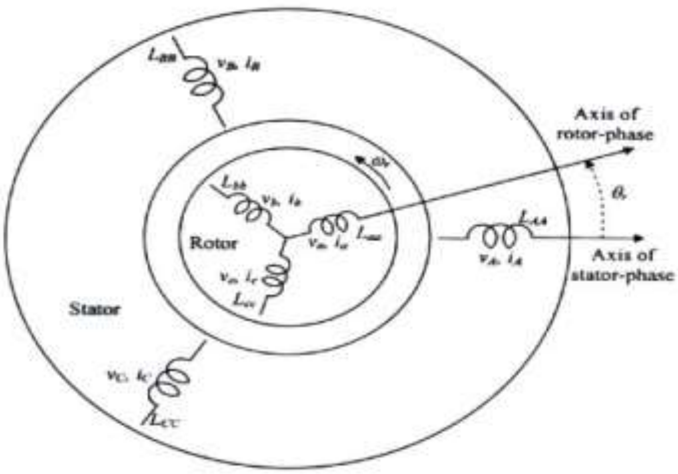

Figure Three phase induction motor

The voltage equations for a three-phase induction machine can be expressed as
Stator equation is

$$V_A = R_A i_A + \frac{d\lambda_A}{dt}$$
$$V_B = R_B i_B + \frac{d\lambda_B}{dt}$$
$$V_C = R_C i_C + \frac{d\lambda_C}{dt}$$
……………(1)

Rotor equation is

$$V_a = R_a i_a + \frac{d\lambda_a}{dt}$$
$$V_b = R_b i_b + \frac{d\lambda_b}{dt}$$
$$V_c = R_c i_c + \frac{d\lambda_c}{dt}$$
…………….(2)

The flux linkages associated with the interactions between stator and rotor windings are represented by
Stator:

$$\lambda_A = L_{AA}i_A + L_{AB}i_B + L_{AC}i_C + L_{Aa}\cos(\theta_r)\, i_a + L_{Ab}\cos(\theta_r + \tfrac{2\pi}{3})\, i_b + L_{Ac}\cos(\theta_r - \tfrac{2\pi}{3})\, i_c$$

$$\lambda_B = L_{BA}i_A + L_{BB}i_B + L_{BC}i_C + L_{Ba}\cos(\theta_r - \frac{2\pi}{3})\, i_a + L_{Bb}\cos(\theta_r)\, i_b + L_{Bc}\cos(\theta_r + \frac{2\pi}{3})\, i_c$$

$$\lambda_C = L_{CA}i_A + L_{CB}i_B + L_{CC}i_C + L_{Ca}\cos(\theta_r + \frac{2\pi}{3})\, i_a + L_{Cb}\cos(\theta_r - \frac{2\pi}{3})\, i_b + L_{Cc}\cos(\theta_r)\, i_c$$

…………(3)

Rotor

$$\lambda_a = L_{aA}\cos(\theta_r)\, i_A + L_{aB}\cos(\theta_r + \frac{2\pi}{3})\, i_B + L_{aC}\cos(\theta_r - \frac{2\pi}{3})\, i_C + L_{Aa}i_a + L_{Ab}i_b + L_{Ac}i_c$$

$$\lambda_b = L_{bA}\cos(\theta_r + \frac{2\pi}{3})\, i_A + L_{aB}\cos(\theta_r)\, i_B + L_{aC}\cos(\theta_r - \frac{2\pi}{3})\, i_C + L_{ba}i_a + L_{bb}i_b + L_{bc}i_c$$

$$\lambda_c = L_{bA}\cos(\theta_r - \frac{2\pi}{3})\, i_A + L_{cB}\cos(\theta_r + \frac{2\pi}{3})\, i_B + L_{cC}\cos(\theta_r)\, i_C + L_{ca}i_a + L_{cb}i_b + L_{cc}i_c$$

………..(4)

The electromechanical torque equation is [10],

$$T_e = -\frac{1}{2}\begin{bmatrix} i_A\left\{i_a[L_{Aa}+L_{aA}](\sin\theta_r) + i_b\,[L_{Ab}+L_{bA}]\sin(\theta_r+\frac{2\pi}{3}) + i_c[L_{Ac}+L_{cA}](\sin\theta_r - \frac{2\pi}{3})\right\} \\ +i_B\left\{i_a[L_{Ba}+L_{aB}](\sin\theta_r - \frac{2\pi}{3}) + i_b\,[L_{Bb}+L_{bB}]\sin(\theta_r) + i_c[L_{Bc}+L_{cB}](\sin\theta_r + \frac{2\pi}{3})\right\} \\ +i_C\left\{i_a[L_{Ca}+L_{aC}](\sin\theta_r + \frac{2\pi}{3}) + i_b\,[L_{Cb}+L_{bC}]\sin(\theta_r - \frac{2\pi}{3}) + i_c[L_{Cc}+L_{cC}](\sin\theta_r)\right\}\end{bmatrix}$$

……..…(5)

The dynamic load equation is [10],

$$T_e - T_L = J\frac{d\omega_r}{dt} + D\omega_r$$

……..….(6)

$$\frac{d\omega_r}{dt} = \frac{T_e - T_L}{J}$$

…..……(7)

$$\omega_r = \frac{1}{J}\int (T_e - T_L)dt$$

……….(8)

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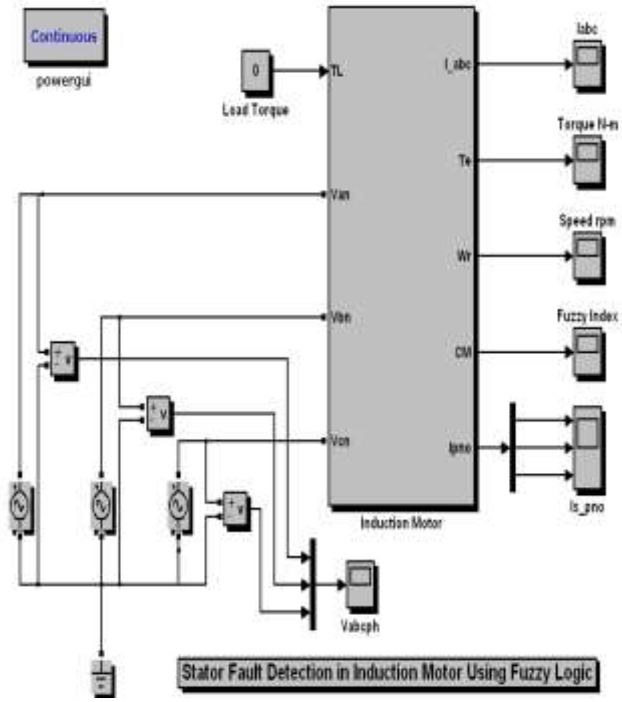


Model and Simulation using MATLAB / Simulink

The implementation of the stationary reference abc model of a three-phase IM using Simulink, using the equations listed in the previous section has been given. Figure 22 shows complete diagram of the IM in the stationary three phase reference frame. The details of the subsystems in the main blocks are given in figure shown above

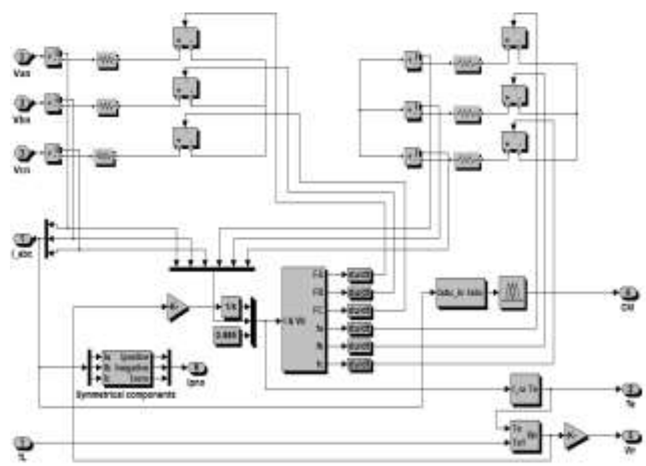


Fig. Equation based induction motor model.

There are many hidden layers in the network. The figure shows two hidden layer. In this network, the number of input

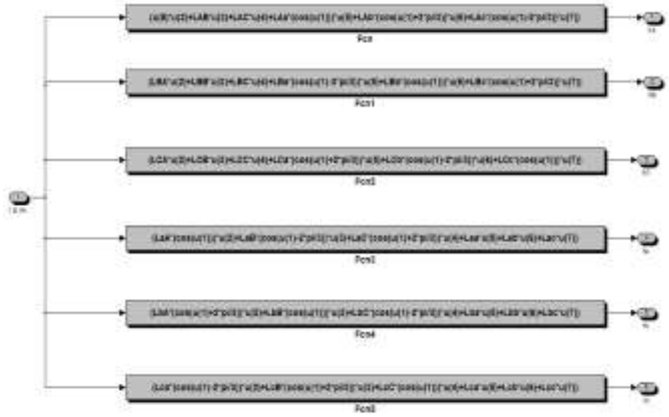


Figure MATLAB subsystem with induction motor equations.

Symmetrical Component Analysis

The presence of phase imbalance and shorted turns in the stator winding of IMs cause predictable harmonics to appear in the signature of line currents and in the axial leakage flux. These changes however, can be small relative to the fundamental. The situation is further complicated because the induced harmonic components can exhibit beating at slip frequency or at a low integer multiple of slip frequency. This means that the detection of changes in the amplitude of such components can be unreliable, since it both frequency and time dependant. To overcome these drawbacks, the symmetrical component theory, and the approach is quite general, allowing for any asymmetrical arrangement of stator winding faults. From the relation of the negative and positive sequence currents to that of slip and torque, when the machine is subjected to different operating situations, the faults can be diagnosed. An unbalanced system of related phasors are resolved in n systems of balanced phasors (the symmetrical components of the original phasors. In symmetrically wound machines there is no reaction between the different sequence quantities, if balanced voltages are applied to the stator, only balanced currents of the same sequence will flow. Due to the mutual winding coupling and other effects, the impedance displayed by machines will be different when exited by different sequence sources. Impedance (per phase) of the positive sequence network will be different from those of negative and zero sequence networks.
The expression for unbalanced phasors as a function of the balanced phasor components are [10]

$$V_A = V_{A0} + V_{A1} + V_{A2}$$
$$V_B = V_{B0} + V_{B1} + V_{B2}$$
$$V_C = V_{C0} + V_{C1} + V_{C2}$$

The positive, negative, and zero sequence vector components of any phase always have the angular relationship with respect to one another [10].

$$V_{A0} = (V_A + V_B + V_C)/3$$
$$V_{A1} = (V_A + aV_B + a^2V_C)/3$$
$$V_{A2} = (V_A + a^2V_B + aV_C)/3$$

$$\begin{pmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix}$$

a=$e^{(\frac{j2\pi}{3})}$

If suppose C phase is open and the motor is running under steady speed. Then Va and Vb are the remaining voltages and they produce equal and opposite line currents Ia and Ib, which increase to around 1.73 to 2.00 times that of the normal. The back EMF generated in the machine armature will be approximately balanced in all three phases, since both the stator windings and rotor have distributed conductors. If stator resistance is ignored, the internal voltage Vma and Vmb of phase A and B respectively will add vectorially with the respective stator leakage reactance voltage drops Vsa and Vsb to equal the applied voltages Va and Vb. For ungrounded neutral, zero-sequence current is neglected. The negative sequence voltages produce currents which are limited by impedance that closely approximate those that apply when the motor is started. This negative-sequence current results in the production of counter torque. To compensate negative torque produced the positive sequence current increases. The motor slip increases to allow the additional positive torque to develop. The similar approach can be applied for the turn faults too.

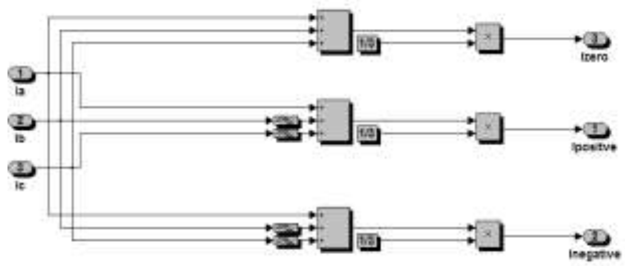
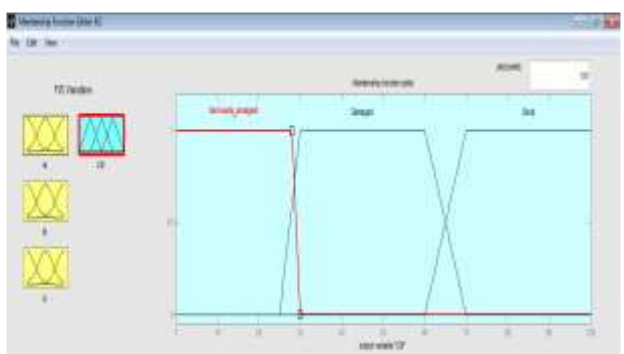


Figure MATLAB subsystem for symmetrical component analysis.

Fuzzy Control

In the motor fault diagnosis process, time domain current signals are captured from current sensors. The expert system for diagnosis then uses both time domain and frequency domain signals to study condition of motor and locate what faults are present. Experienced engineers are often required to interpret measurement data that are frequently inconclusive. A FL approach may help to diagnose IM faults. FL is reminiscent of human thinking process enabling decisions to be judged on vague information. FL allows items to be described with certain membership degree in a set. For fault diagnosis, there are many situations in which a system is not "Good" or "Damaged", but may fall into some internal range. According to the fact that IM condition analysis is a fuzzy concept, the motor condition is described using linguistic variables. Fuzzy subsets and the respective membership functions represent stator current amplitudes. A knowledge base, comprising rule base is built to support the fuzzy inference. The IM condition is diagnosed using a compositional rule of fuzzy inference. The obtained results indicate that the proposed FL approach is capable of highly accurate diagnosis. Humans express knowledge (like an electrical machine referred as "somewhat secure", "little overloaded"). This linguistic input can be represented by a fuzzy system. The internal structure of fuzzy controller is shown in figure 26. Stator current signature contains potential fault information. Fuzzy systems rely on a set of rules [10].

$I_a = \{ \mu_{ia} \left(I_{aj}\right) \Sigma I_a \}$
$I_b = \{ \mu_{ib} \left(I_{bj}\right) \Sigma I_b \}$
$I_c = \{ \mu_{ic} \left(I_{cj}\right) \Sigma I_c \}$



CM = $\{ \mu_{cm}(cm_j) \Sigma CM \}$

These rules, with the fuzzy input, i.e. like the natural way that where Iaj, Ibj, Icj and CM are elements of the discrete universe of discourse Ia , Ib, Ic and CM, the optimized rule base has been developed so as to cover all the healthy and the faulty conditions of the motor.

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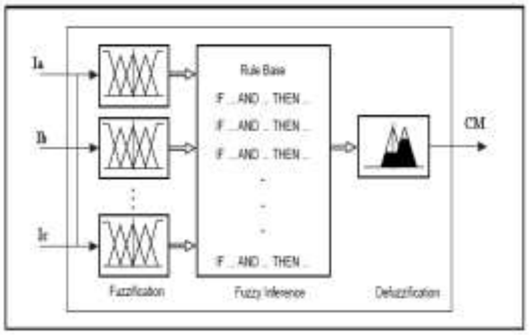

Figure Internal structure of Fuzzy Controller [10]

In this case the Ia, Ib, and Ic are input variables to the fuzzy system. The stator condition, CM is chosen as output variable. All the inputs and outputs are defined by fuzzy set theory. The input variables are interpreted as linguistic variables, with Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS) and Positive Medium (PM). Similarly the output variable stator condition (CM) is interpreted as linguistic variables, with Good, Damaged, and Seriously Damaged. Membership functions and fuzzy rules are constructed by observing the data set. There are 31 if-then rules used with the membership function for input and output variables are shown in figure 27 and figure 28 respectively.

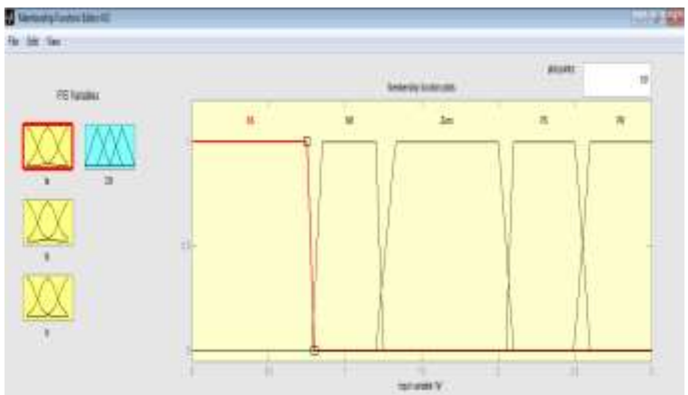

Figure Fuzzy membership functions for stator currents

***Figure Fuzzy membership functions for condition of mo**tor*

Rule Base
SD: Seriously Damaged
D: Damaged
G: Good

1. If Ia is NS then CM is SD
2. If Ib is NS then CM is SD
3. If Ic is NS then CM is SD
4. If Ia is PM then CM is SD
5. If Ib is PM then CM is SD
6. If Ic is PM then CM is SD
7. If Ia is NM and Ib is NM and Ic is NM then CM is G
8. If Ia is NM and Ib is NM and Ic is Zero then CM is D.
9. If Ia is NM and Ib is NM and Ic is PS then CM is D
10. If Ia is NM and Ib is Zero and Ic is NM then CM is D
11. If Ia is NM and Ib is PS and Ic is NM then CM is D
12. If Ia is Zero and Ib is NM and Ic is NM then CM is D
13. If Ia is PS and Ib is NM and Ic is NM then CM is D

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14. If Ia is NM and Ib is Zero and Ic is Zero then CM is D
15. If Ia is NM and Ib is Zero and Ic is PS then CM is SD
16. If Ia is NM and Ib is PS and Ic is Zero then CM is SD
17. If Ia is NM and Ib is PS and Ic is PS then CM is D
18. If Ia is Zero and Ib is NM and Ic is Zero then CM is D
19. If Ia is Zero and Ib is NM and Ic is PS then CM is SD
20. If Ia is PS and Ib is NM and Ic is Zero then CM is SD
21. If Ia is PS and Ib is NM and Ic is PS then CM is D
22. If Ia is Zero and Ib is Zero and Ic is NM then CM is D
23. If Ia is PS and Ib is Zero and Ic is NM then CM is SD
24. If Ia is Zero and Ib is PS and Ic is NM then CM is SD
25. If Ia is Zero and Ib is PS and Ic is Zero then CM is Dbn
26. If Ia is Zero and Ib is PS and Ic is PS then CM is D
27. If Ia is Zero and Ib is Zero and Ic is PS then CM is D
28. If Ia is PS and Ib is Zero and Ic is Zero then CM is D
29. If Ia is Zero and Ib is Zero and Ic is Zero then CM is G
30. If Ia is PS and Ib is PS and Ic is Zero then CM is G
31. If Ia is Zero and Ib is PS and Ic is PS then CM is G.

Defuzzification is defined as the conversion of fuzzy output to crisp output. There are many types of defuzzification methods available. Here we used Center of Area (COA) method for defuzzification. Despite its complexity it is more popularly used because, if the areas of two or more contributing rules overlap, the overlapping area is counted only once.

Output of FL Controller
1. Good ----- 70 TO 100
2. Damaged ----- 30 To 70
3. Seriously Damaged ----- 0 To 30

The output of the fuzzy controller is used as the command signal for the closed loop operations. If the fuzzy controller output is Good, then the program goes for next set of data to be acquired. Meanwhile if the operator wants, the data like three phase current, three phase voltage, frequency of input voltage, power factor, total harmonic distortion of both the current and voltage and the state of the motor can be stored in a file.

If any incipient faults are slight voltage unbalance occurs, then the output of the fuzzy controller will go Damaged. Immediately the fault data and the current spectrum are stored in a file for analysis purpose with time as long as fault persists. At the same time a warning indication will be given to the operator, and a beep sound will be generated at the central processing unit of the computer to alert the operator at the shop as well as the control room engineer. The front panel of the monitoring system will also display the possible cause for the damaged state of the motor. The instantaneous current and voltage waveforms, and the spectrum of the current can be stored as a HTML file to find the root cause of the fault.

For the severe faults such as open phase, open coil, single line to ground short and line to line to short, the fuzzy controller output will be seriously damaged. In this state the machine should not be allowed to operate any further. Whenever the fuzzy controller output goes seriously damaged, the machine will be isolated from the supply and the instantaneous fault data are stored, also the front panel of the monitoring system will display the possible cause seriously damaged state of the motor. After performing the above said operations the program will be stopped.

II. RESULT & ANALYSIS

Normal Operation

For the values given in section 5.4.1 and using a simulation stop time of 1.0 seconds, the motor was simulated during starting from rest with rated voltage applied and no mechanical load. Figure 29 and 30 shows the Stator current and health of IM, Stator input voltage, speed and torque, symmetrical components of stator current, symmetrical components of stator induced voltage, symmetrical components of stator input voltage are shown. From these results it can be concluded that after the transient period is over, the health of the motor is good, and there is no negative sequence component in both stator induced voltage and stator current.

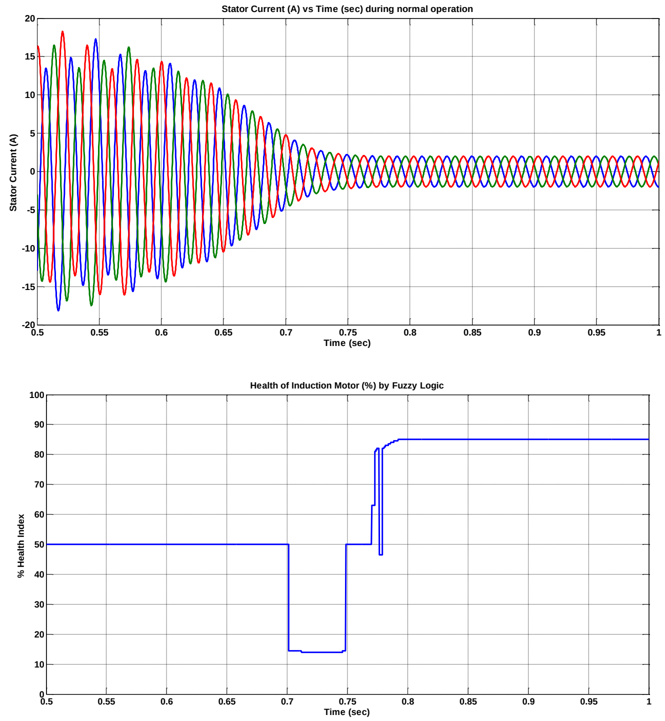


Figure Three phase Stator currents and Percentage Health of Induction motor (Normal Operation)

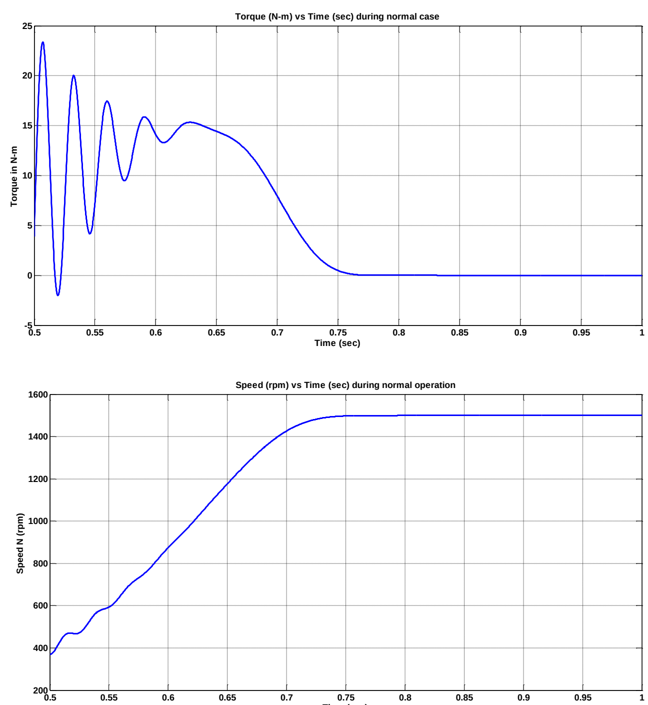


Figure : Developed Torque and Speed of Induction motor (Normal Operation)

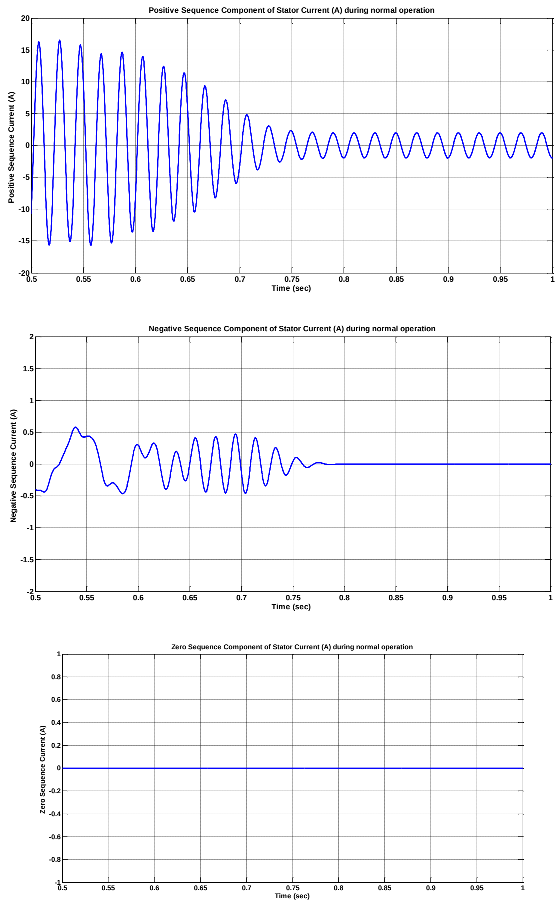


Figure. Positive, Negative and Zero sequence components of stator current (Normal Operation)

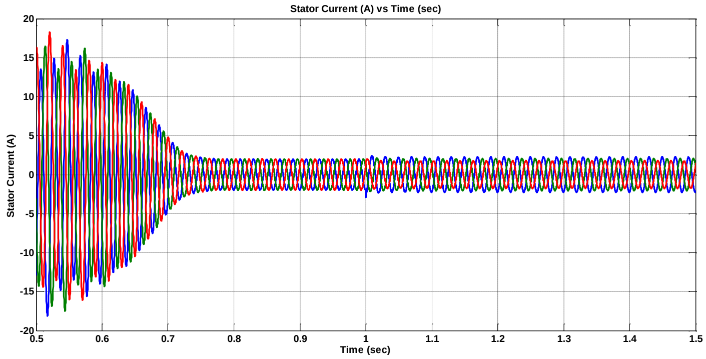
Turn To Turn short in one phase winding

Simulation for the short circuit in some part of the R phase winding has been carried out. At this condition the value of the stator resistance at short circuit fault is equal to R = 13.1 Ω, we can find the value of the inductance at the fault state by using the ratio between the value of the resistance at both state (normal and fault). Thus the value of the inductance is,

$$\frac{R_{Stator,normal}}{R_{Stator,fault}} = n = \frac{L_{Stator,normal}}{L_{Stator,fault}}$$

$$\frac{15.3}{13.1} = \frac{0.585}{L_{stator,fault}} \Rightarrow \therefore L_{stator,fault} \approx 0.5H$$

Replacing the values of the stator resistance and stator self-inductance in phase R by these values the results can be obtained. Figure 32, 33 and 34 shows the stator current and health of IM, speed and torque, symmetrical components Istator, symmetrical components of voltage induced in stator winding, are shown. The simulation is started up with normal state parameters. After obtaining steady state at 0.78 second the turn fault has been created by changing the above said parameters at 1 sec. From these results it can be concluded that during normal operation (before fault), the motor is in Good health, with no negative sequence component in both stator induced voltage and stator current. when the fault is created the Istator becomes unbalanced, and the health of the IM goes from seriously damaged to Damaged state, and it is found that there is a presence of negative sequence component in stator current and induced voltage variations during fault conditions.



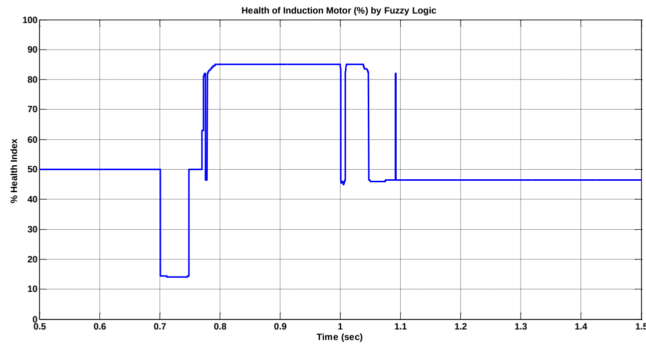
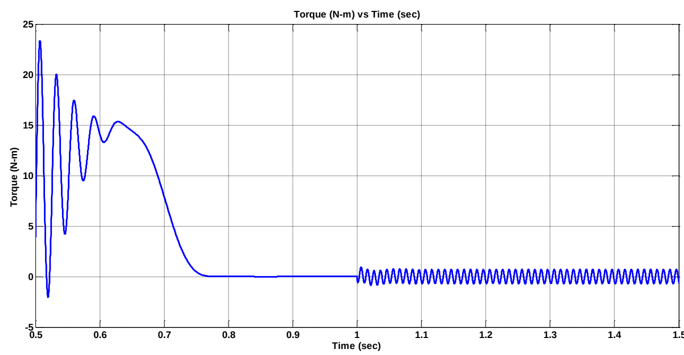


Figure . Three phase Stator currents and Percentage Health of IM (Turn to turn short operation)



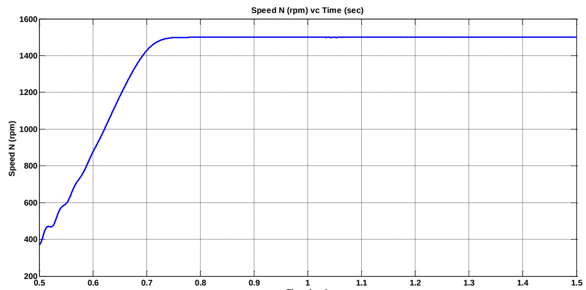


Figure : Developed Torque and Speed of IM (Turn to turn short operation)

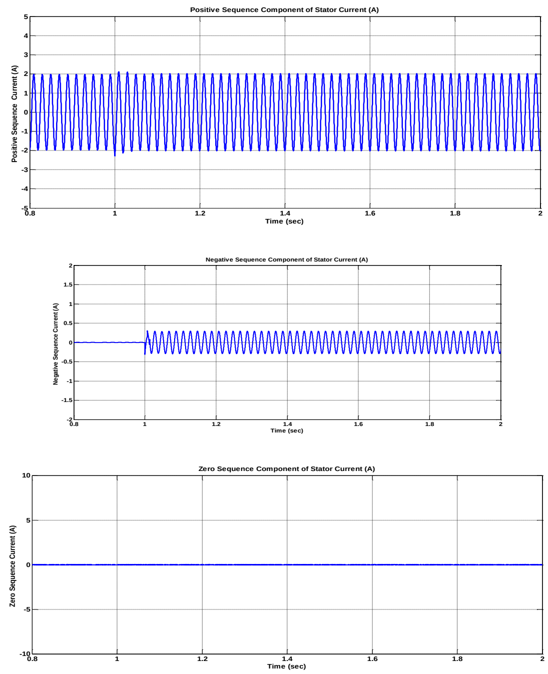


Figure . Symmetrical component waveforms of stator current (Turn to turn short operation)

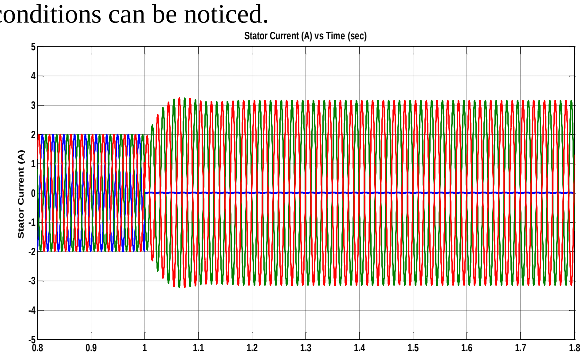
Break in stator winding

With simulation of a break in the stator winding at R phase, it is not possible to apply a break in the phase with the value of the Rstator and the Lstator to infinity or very high. It is assumed that the value of the Rstator is very high and corresponding to this value we can calculate the value of the inductance by this equation:

$$\frac{R_{Stator,normal}}{R_{Stator,fault}} = n = \frac{L_{Stator,normal}}{L_{Stator,fault}}$$

$$\frac{15.3}{10000} = \frac{0.585}{L_{stator,fault}} \Rightarrow \therefore L_{stator,fault} \approx 382.35H$$

Replacing the values of the stator resistance and stator self-inductance in phase R by these values, the fault state results can be obtained. Figure 35, 36 and 37 shows the Stator current and health of IM, speed and torque, Istator symmetrical components, symmetrical components of voltage induced in the stator, are shown. The simulation is using normal state parameters. With steady state obtained at 0.78 second the break in winding fault has been created at 1 sec by changing the above said parameters. From the results it can be observed that during normal operation, the motor has Good health, and there is no negative sequence component in both stator induced voltage and Istator. When the fault is created the Istator becomes unbalanced, and the health of the IM goes to seriously damaged and finally settles to the same state, and the presence of negative sequence component in both stator induced voltage and Istator variations during fault conditions can be noticed.



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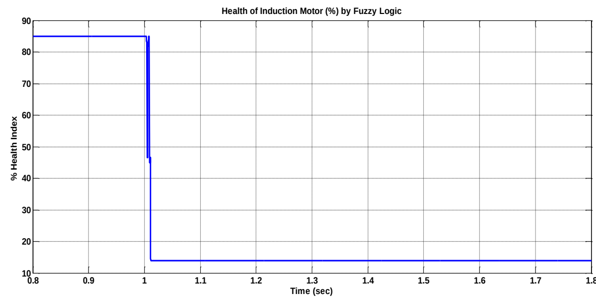


Figure : Stator current and Percentage health of IM (Break in winding)

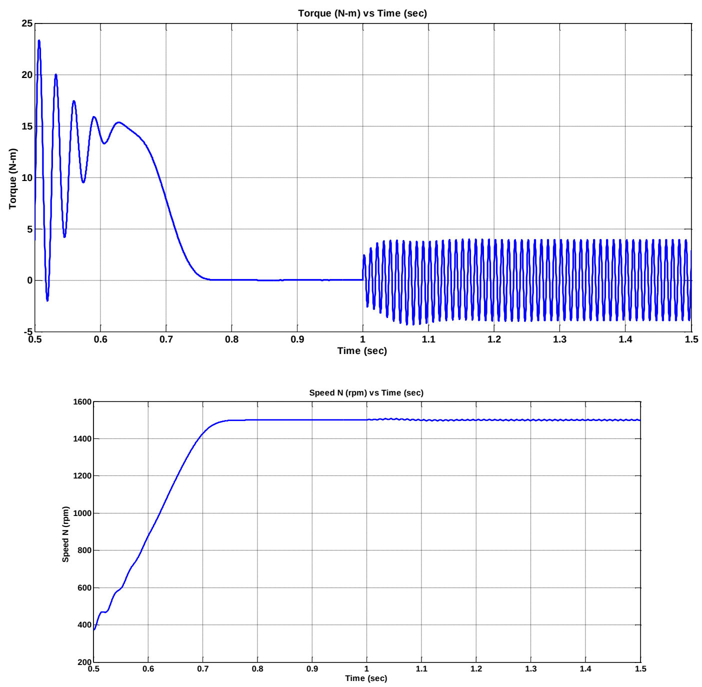
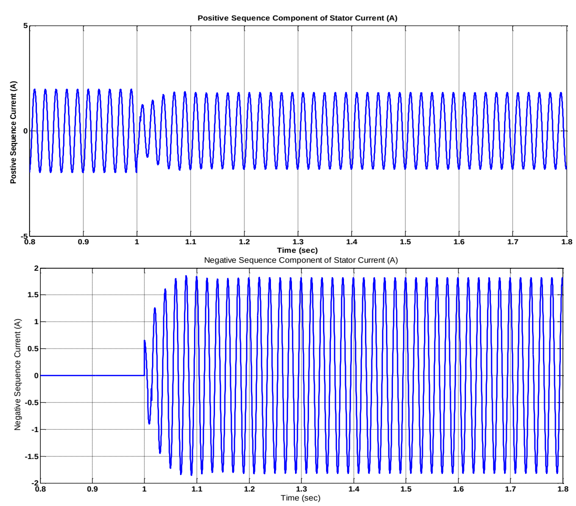


Figure . Developed Torque and Speed of IM (Break in stator winding operation)



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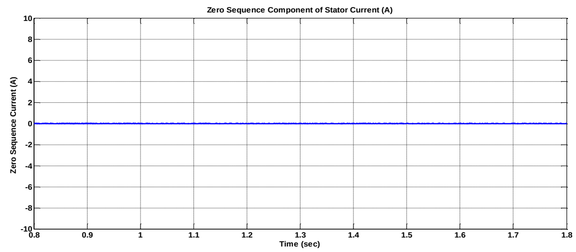

Figure . Symmetrical component waveform of stator current (Break in winding)

Unbalance in input voltage

The simulation of IM with voltage unbalance can be simulated by simply varying the magnitude of the voltage magnitude in one of the phases, no other parameters need to be changed. As in the previous case, the machine is started up with normal value, and at 0.78 second, the current takes its steady state value, now the fault is produced by changing the B phase voltage. In current case a 6% of the rated voltage in C phase was reduced to create unbalance. Figure 38, 39 and 40 shows the Stator current and health of IM, speed and torque, symmetrical components of Istator, stator induced voltage symmetrical components, and symmetrical components of voltage input are shown. The simulation is using normal state parameters. With steady state at 0.78 second the turn fault has been created at 1 sec by changing the magnitude of B phase voltage. From results it can be observed that during normal operation, the motor is in Good health, and there is no negative sequence component in both stator induced voltage and Istator. As soon as the fault is created the stator current becomes unbalanced, and the health of the IM goes from seriously damaged to final Damaged state, and we can observe that negative sequence component is present in both stator induced voltage and Istator signature during fault conditions.

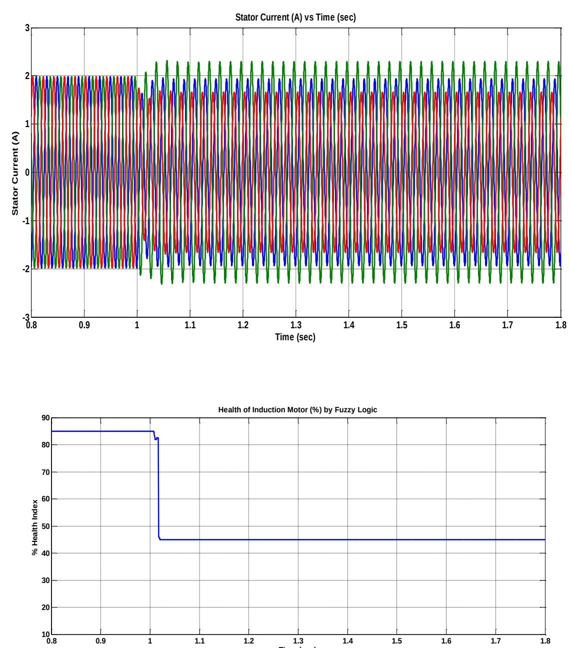

Figure . Stator current and Percentage health of IM (voltage unbalance)

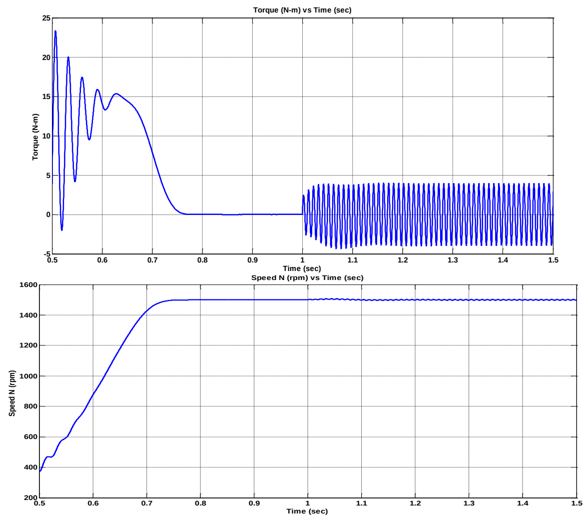

Figure Developed Torque and Speed of IM (Unbalance in voltage operation)

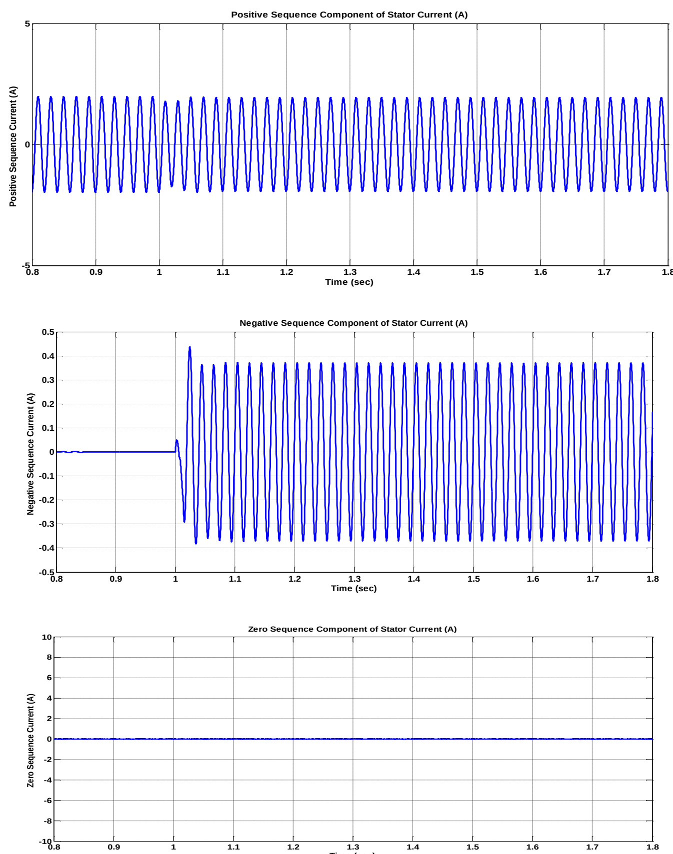

Figure : Symmetrical component waveform of stator current (voltage unbalance)

Open Phase fault

In this case after normal startup, at 0.78 second, R phase was open circuited at 1 sec and the corresponding results are shown in figures shows the condition monitoring of motor

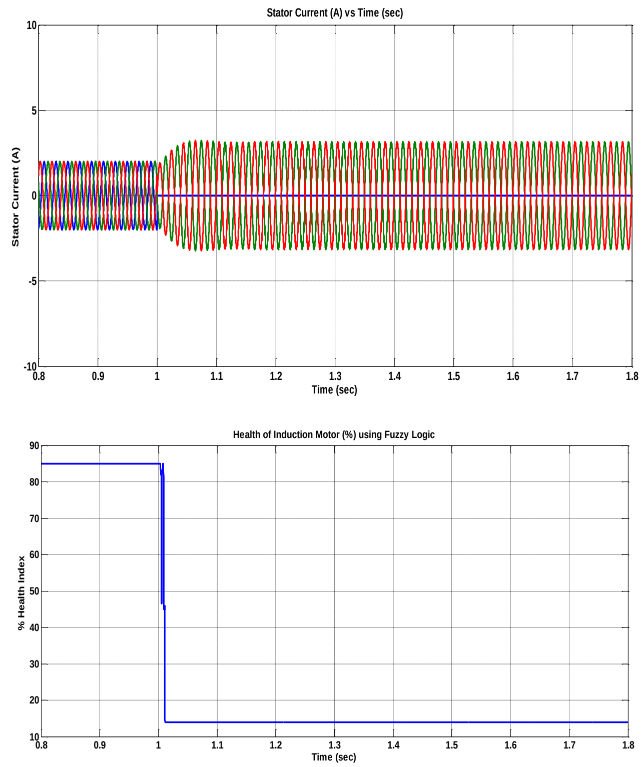

Figure Stator current and Percentage health of IM (one phase open)

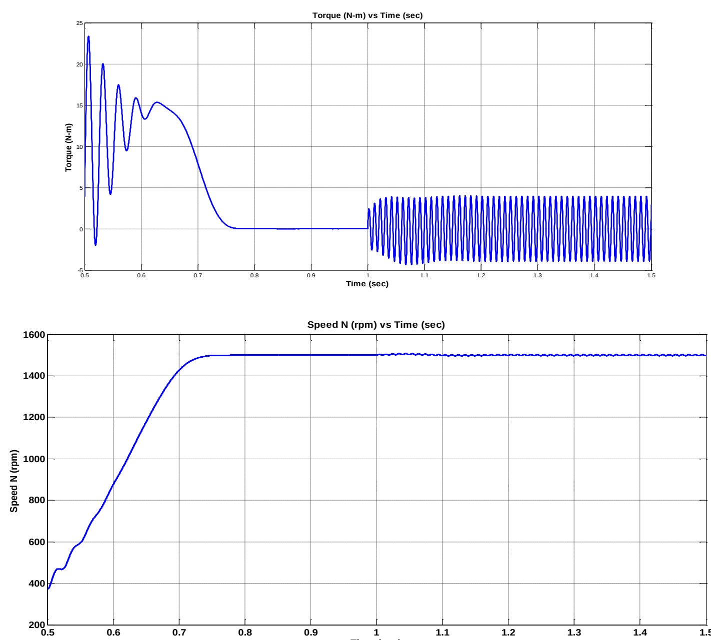

Figure : Developed Torque and Speed of IM (One phase open operation)

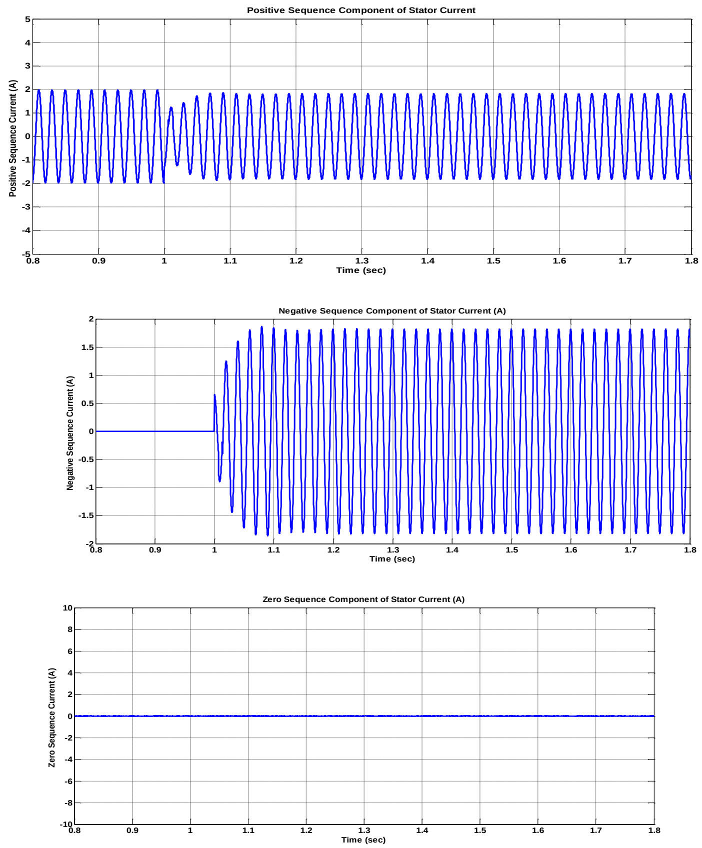

Figure . Symmetrical component waveform of stator current (one phase open)

III. CONCLUSION

Many researches dealt with the problem of IMs fault detection and diagnosis. The major difficulty is the lack of an accurate model describing a motor fault. Moreover, experienced engineers are often required to interpret measurement data that are frequently inconclusive. A FL approach may help to diagnose IM faults. In fact, FL is reminiscent of human thinking and natural language enabling vague information based decision making. Therefore, this project applies FL to IMs fault detection and diagnosis. The motor condition is described using linguistic variables. Fuzzy subsets and the respective membership functions describe amplitude of stator current. A knowledge base, comprising of data bases and rules, is built to justify the fuzzy inference. The IM condition is diagnosed using a compositional rule of fuzzy inference.

FL based measurement and health evaluation system has been developed and implemented. This application allows fast failure state estimation for different stator faults on the IM. The more detailed analysis to point out the difficult machine conditions under different stator fault conditions of IM can be performed. This is a versatile technique for fault analysis and condition monitoring of motors. It solves the shutdown problems and gives safe working environment in continuous industrial processes

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