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Induction Motor Stator Fault Detection And Health Monitoring Using Fuzzy Logic

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Abstract: Condition monitoring of induction motors is an established maintenance strategy for the detection of incipient faults as to avoid the unexpected failure. Now day's artificial intelligence techniques are being preferred over traditional protective relays for the condition monitoring of induction motors. In this paper an attempt has been made to apply Fuzzy Logic (FL) based health monitoring of induction motor. Induction motor modeling is done in MATLAB and different stator faults are simulated. Fuzzy Logic based measurement and health evaluation system has been developed and implemented.

Keywords: component; Artificial Intelligence, Fuzzy Logic, Induction Motor.

I. INTRODUCTION

The three phase Induction motors due to their simple construction, high reliability and low cost, have dominated in the field of electromechanical energy conversion by having more than 75% of motors in use. Though the probability of breakdowns of Induction motors is very low, the fault diagnosis has become almost indispensable. Particularly when they are working in sophisticated automated production lines. To decrease the machine down time and improve stability on line diagnostic features are to be necessarily incorporated with the drives. In modern industry lots of machines depend on mutual operation, and the cost of unexpected breakdowns is very high. Thus condition monitoring techniques comprising of fault diagnosis and prognosis are of great concern in industry and are gaining increasing attention.

The Artificial Intelligence (AI) techniques have certain distinct advantages over traditional condition monitoring approaches. In the present paper an effort has been made to apply fuzzy logic based approach for induction motor condition monitoring. These systems can be integrated together and also with other traditional techniques.

II. MODELING AND SIMULATION OF THREE PHASE IM

Simulation can be very useful in many scientific studies that proceed as follows:

- Observing the physical system.
- Formulating a hypothesis or mathematical model to explain the observation.
- Predicting the behavior of the system from solutions or properties of the mathematical model.
- Testing the validity of the hypothesis or mathematical model.

The three-phase induction motor model has been derived 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.

A. Induction Machine Equations

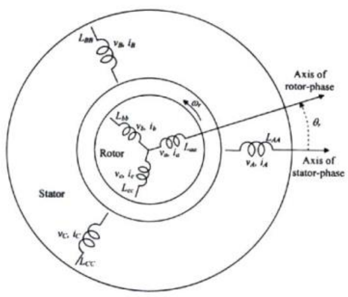

Fig. 1 Two dimensional diagram of three-phase IM with stator and rotor windings [8].

Stator equation is, $V_A = R_A i_A + \frac{d\lambda_A}{dt}$;$V_B = R_B i_B + \frac{d\lambda_B}{dt}$;$V_C = R_C i_C + \frac{d\lambda_C}{dt}$.

Rotor equation is, $V_a = R_a i_a + \frac{d\lambda_a}{dt}$;$V_b = R_b i_b + \frac{d\lambda_b}{dt}$;$V_c = R_c i_c + \frac{d\lambda_c}{dt}$

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

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

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

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

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

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

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

The electromechanical torque equation is,

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

The dynamic load equation is: $T_e - T_L = J\frac{d\omega_r}{dt} + D\omega_r$; $\frac{d\omega_r}{dt} = \frac{T_e - T_L}{J}$; $\omega_r = \frac{1}{J}\int(T_e - T_L)dt$

B. Induction Machine model in a three-phase reference frame

When induction machines are expressed in three-phase axes, many of the inductances are function of the rotor displacement and therefore functions of rotor speed and time as shown in the following

Stator Inductances: It is assumed that the air gap of the induction machine is uniform and the stator and rotor windings are sinusoidally distributed, all the stator self-inductances are identical. $L_{AA} = L_{BB} = L_{CC} = L_{ls} = L_{ms}$

The mutual inductance between any two stator windings is the same due to symmetry

$L_{AB} = L_{BA} = -0.5L_{ms}$; $L_{BC} = L_{CB} = -0.5L_{ms}$; $L_{CA} = L_{AC} = -0.5L_{ms}$

Rotor Inductances:

$$L_{aa} = L_{bb} = L_{cc} = L_{lr} = L_{mr},\ L_{ab} = L_{ba} = -0.5L_{mr}\ ;L_{bc} = L_{cb} = -0.5L_{mr}, L_{ca} = L_{ac} = -0.5L_{mr}$$

In the same manner to that given for the stator, the rotor self-inductances and mutual inductances are:

$L_{Ac} = L_{Ba} = L_{Cb} = L_{msr}\cos(\theta_r - 120^\circ)$,$L_{Ab} = L_{Bc} = L_{Ca} = L_{msr}\cos(\theta_r + 120^\circ)$,$L_{Aa} = L_{Bb} = L_{Cc} = L_{msr}\cos(\theta_r^\circ)$

The mutual inductance between a stator winding and any rotor winding varies sinusoidally with rotor position.

III. INDUCTION MOTOR MODEL IMPLEMENTATION WITH MATLAB/SIMULINK

In this section, the implementation of the stationary reference abc model of a three-phase induction motor using Simulink, using the equations listed in the previous section has been given. Figure 4.shows an overall diagram of the induction motor in the stationary three-phase reference frame. The details of the subsystems in the main blocks are given in figure

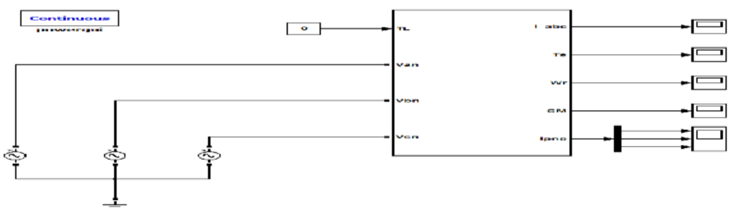

Fig. 2 IM model in Simulink/ MATLAB.

TABLE I

SR. No	Parameter	Rating
1	Rated Voltage (V)	380V
2	Frequency (f)	50 Hz
3	Stator Resistance (R_{stator})	15.3Ω
4	Rotor Resistance (R_{rotor})	7.46Ω
5	The stator and rotor self-inductances are equal to $L_{stator} = L_{rotor} = L_{leakage}+L_{mutual}$	0.035+0.55 =0.585H
6	The mutual inductance between any two stator and any two rotor windings is equal to $L_{ss,mutual} = L_{rr,mutual} = -0.5L_{mutual}$	-0.275H
7	The mutual inductance between a stator winding and any rotor winding is equal to $L_{sr,mutual} = L_{mutual}$	0.55H
8	Number of Poles (P)	4
9	Inertial constant (J)	0.023 kg.m^2

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 [8].

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.

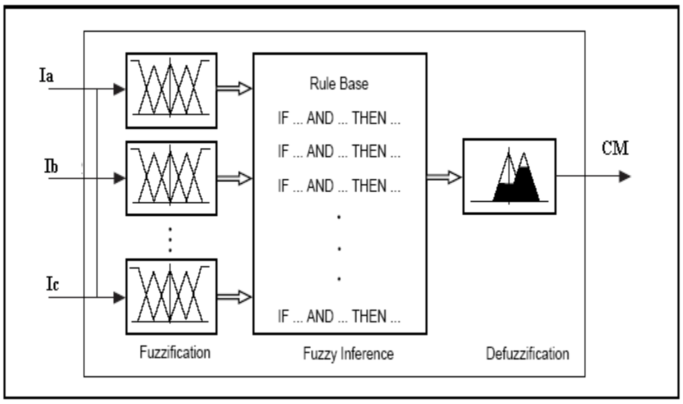

Fig. 3 Internal structure of Fuzzy Controller

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. Output of FL Controller in percentage health index Good (70-100), Damaged (30-70 %), Seriously Damaged (0-30) [8].

IV. SIMULATION AND RESULTS

A. Normal operation:

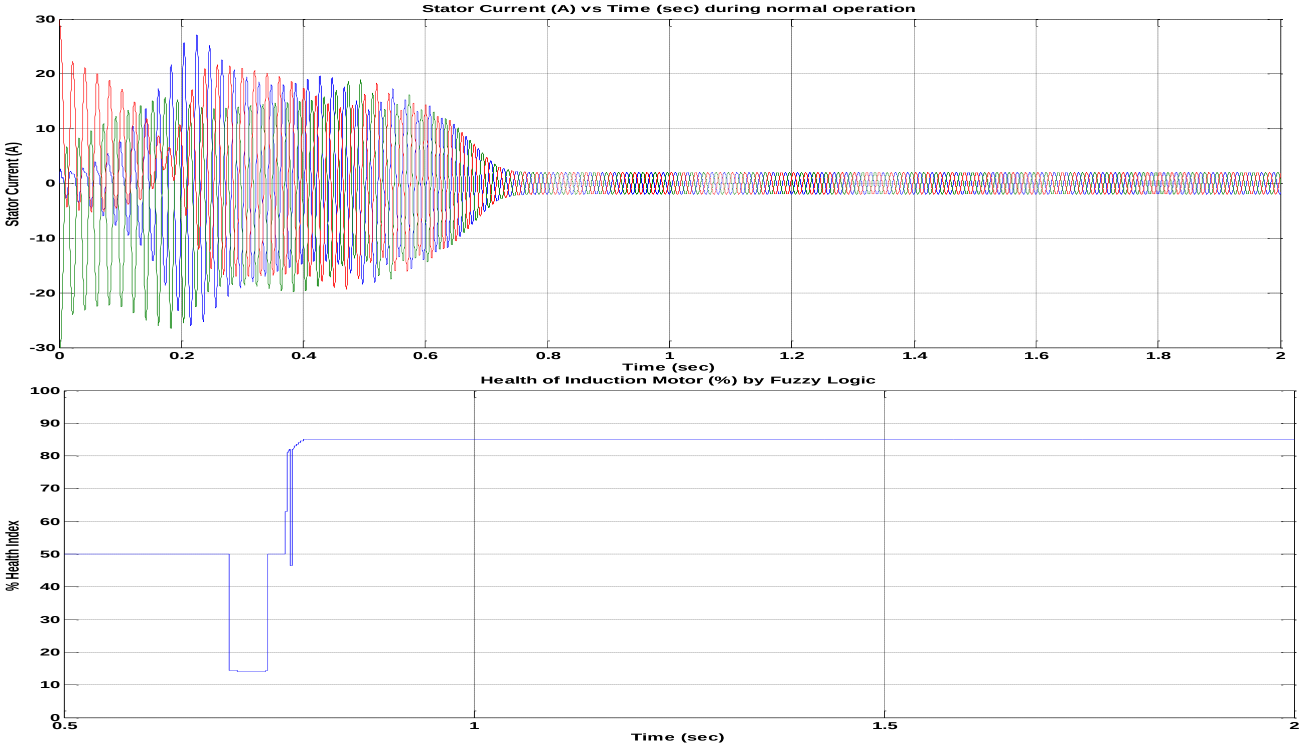

Fig. 4 Three phase Stator currents and Percentage Health of Induction motor (Normal Operation)

System is simulated up to 2.0 seconds, from rest with rated voltage applied and no mechanical load. 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.

B. Turn-Turn short in one phase winding

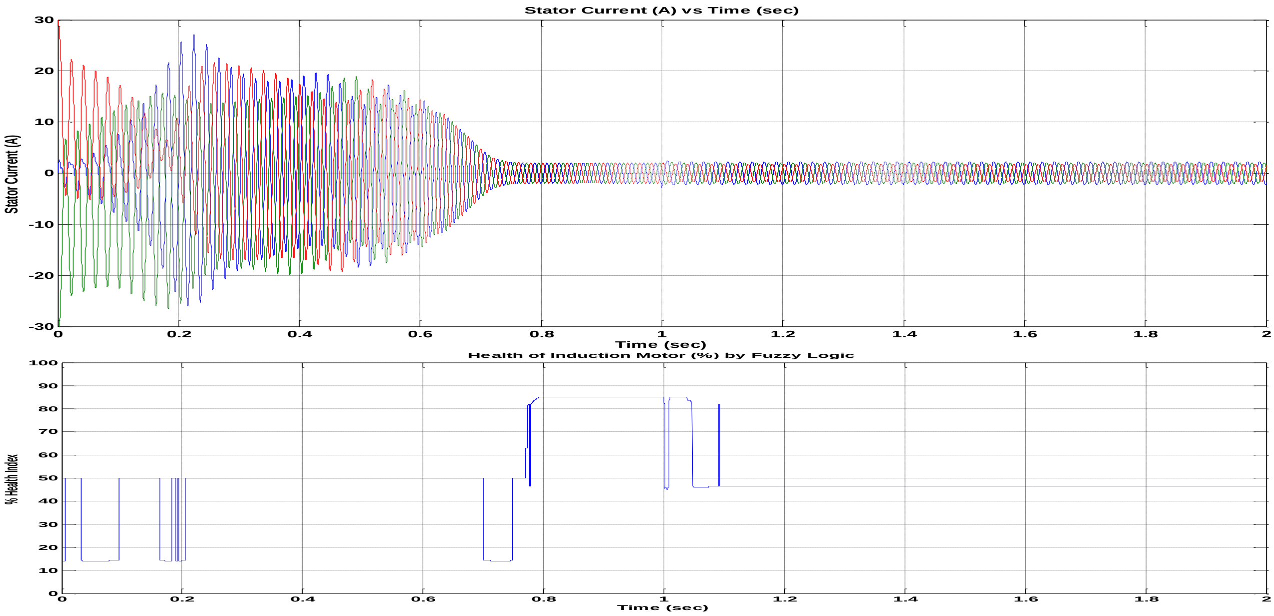

Fig. 5 Three phase Stator currents and Percentage Health of Induction motor (Turn to turn short operation)

Simulation for the short circuit in the part of the winding in R phase has been carried out with $R_{stator,\ fault}$ = 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 $L_{stator,\ fault}$ = 0.5 H. After obtaining steady state the turn fault has been created by changing the above said parameters. From these results it can be concluded that during normal operation (before fault), the health of the motor is Good, and there is no negative sequence component in both stator induced voltage and stator current. As soon as the fault is created the stator current becomes unbalanced, and the health of the induction motor goes seriously damaged and finally settles to Damaged state.

C. Break in stator winding

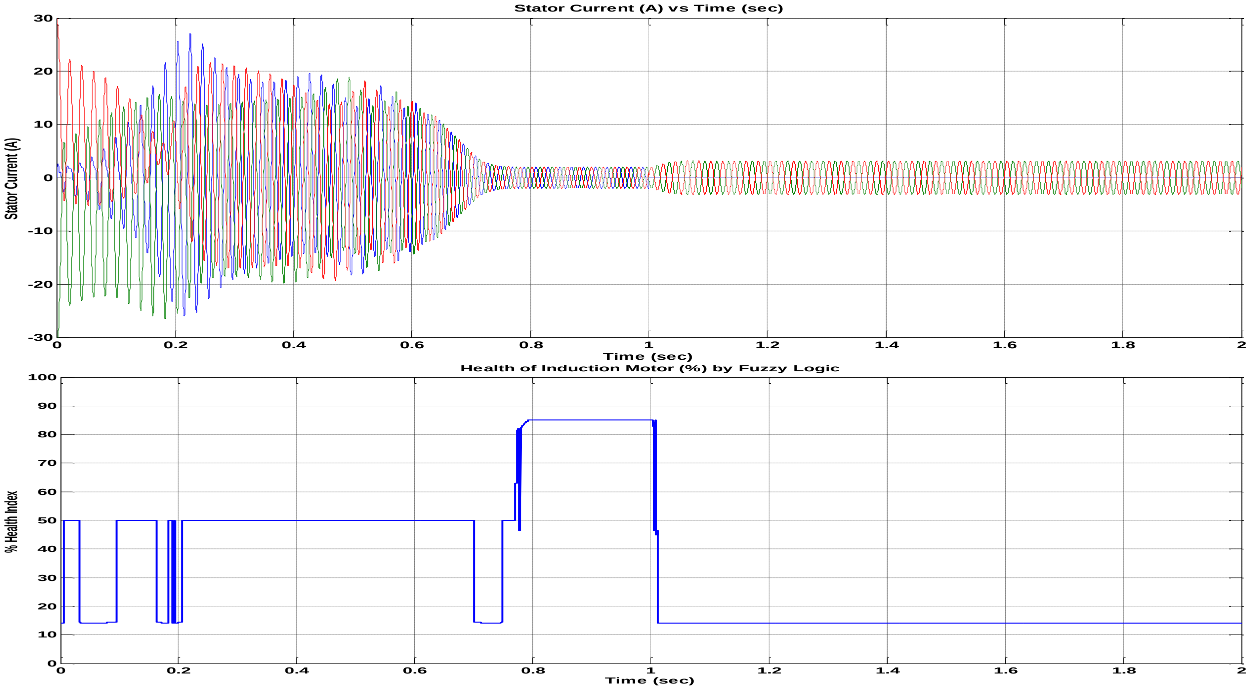

Fig. 6 Three phase Stator currents and Percentage Health of Induction motor (Break in stator winding operation)

For simulation of the break fault in the stator winding at R phase, it is not possible to apply a break in the phase by putting the value of the stator resistance and the stator inductance to infinity. As soon as the fault is created the stator current becomes fully unbalanced, and the health of the induction motor goes seriously damaged and finally settles to the same state, and the presence of negative sequence component in both stator induced voltage and stator current waveforms during fault conditions can be noticed.

D. Unbalanced in input voltage

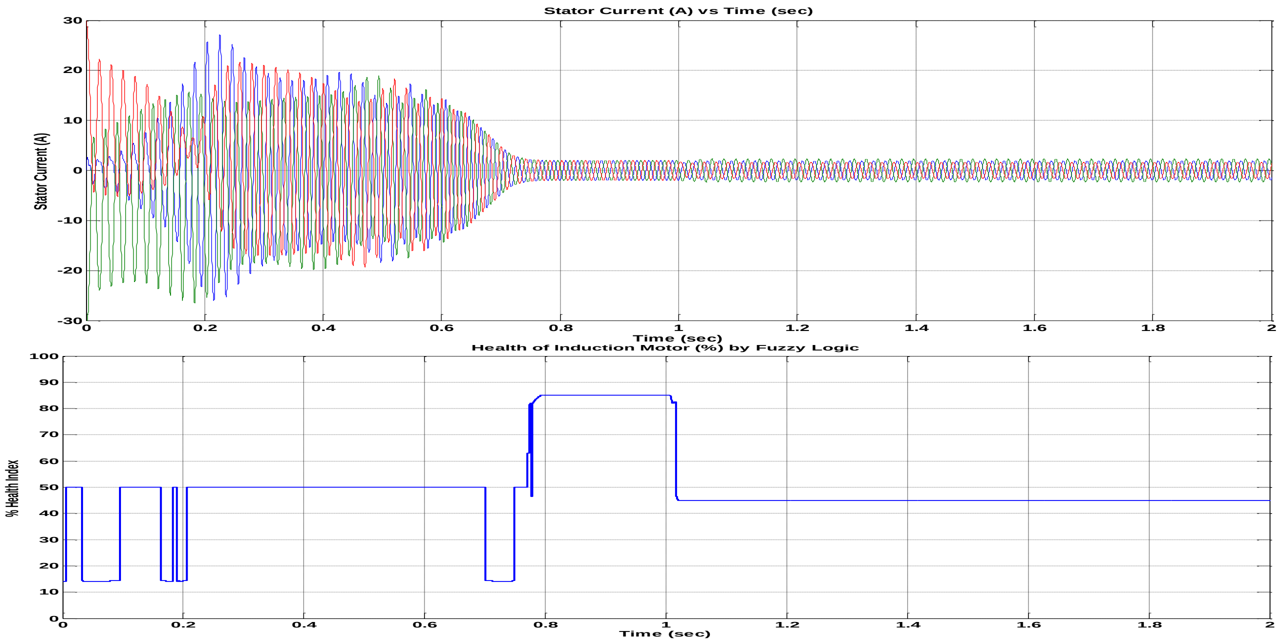

Fig. 7 Three phase Stator currents and Percentage Health of Induction motor (input voltage unbalance)

The simulation of induction motor with voltage unbalance can be simulated by simply varying the voltage magnitude in any one of the phase, no other parameters need to be changed. In this case a 6% of the rated voltage in C phase was reduced to create unbalance. From these results it can be concluded that during normal operation (before fault), the health of the motor is Good, and there is no negative sequence component in both stator induced voltage and stator current. As soon as the fault is created the stator current becomes unbalanced, and the health of the induction motor goes seriously damaged and finally settles to Damaged state.

E. Open phase fault

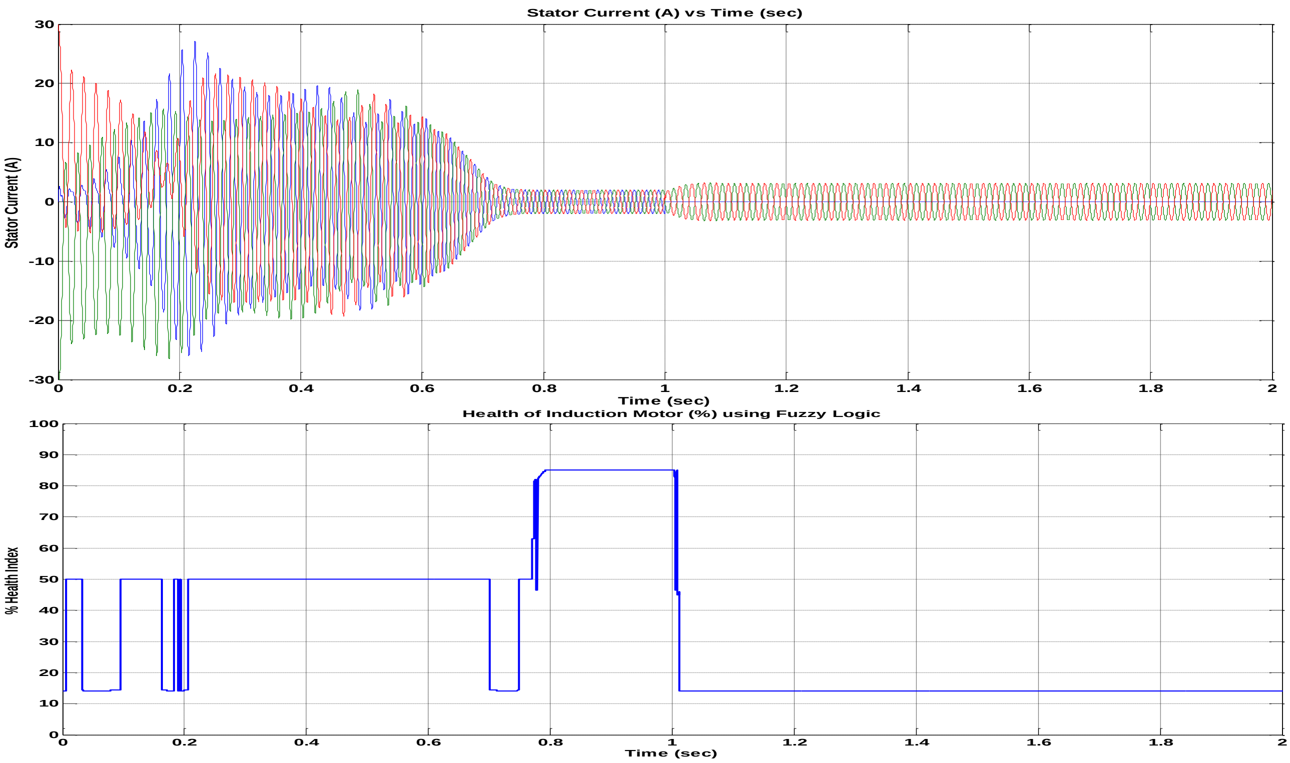

Fig. 8 Three phase Stator currents and Percentage Health of Induction motor (open phase fault)

In this case after normal startup, R phase was open circuited and the corresponding results show the condition monitoring of motor.

CONCLUSION

A MATLAB application software based measurement and health evaluation system (using Fuzzy Logic) has been developed and applied for induction motor stator faults diagnosis. This application allows fast failure state estimation. The more detailed investigation to point out the difficult conditions of the machine under different stator fault conditions of induction motor can be performed. This is a highly versatile technology for condition monitoring and fault analysis of motors. It solves the shutdown Problems and ensures safe working environment in continuous process industry.

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