Modeling and Analysis of Three Phase Induction Motor with Broken Rotor Bar

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Abstract— **Owing to their extensive use and waste presence in different procedures and processes, induction machines are rightly called as the work horses of the industry. Adequate and timely maintenance, fault finding and repair of these machines is a mandatory requirement for efficient working. In literature, extensive work has been presented exploring induction machine faults their symptoms and remedies. Broken rotor bar is one of the highly investigated. Due to the complexity involved in observing this fault, indirect methods to detect its presence are employed. Simulation is a modern tool to analyze machines under different operating conditions. However, in case of a faulty machine, model becomes different as compares to the normal mode. In this paper a three phase induction machine model is presented having broken rotor bars. Moreover, comparative analysis is performed between faulty and healthy case. An easy to comprehend model of an induction motor in *abc* frame is described to understand the parametric change of a faulty model of an induction motor. The implementation of both healthy and faulty model is done using Matlab/Simulink software. First, the healthy motor is simulated and then the results of faulty motor are compared with the healthy motor to understand the change in response of faulty and healthy motor. Consideration is on broken rotor bar fault but other faults like bearing fault, phase imbalance and mechanical faults can also occur because of broken rotor bar. As the motor is the backbone of the process of an industry a short time shut down of a plant is avoided, the method proposed can be helpful in understanding the current and frequency response of an induction motor which can be use to avoid breakdown maintenance.**

I. Introduction

An induction motor is one the most widely used machine in an industrial setup and is one of the most power consumed machine nowadays. There are certain advantages in other machines like DC, PMDC and BLDC but they are considered where there control is an important task to perform but for most of the other application induction motor is of vital importance. As induction motor is one of the machine which need least maintenance it can be used in harsh environment but due to environmental changes, phase imbalance, and ware tare of the motor certain faults occur in an induction machine. These faults are rare and occur not much frequently but can effect the operation or some time production which may results in loss.

Researchers are working on the diagnosis and removal of such faults in which broken rotor bar is one of the important faults. If the faults is not diagnosed it may lead to destruction of motor and surroundings if not removed. So, an early diagnosing of a faults in induction machine should be adopted so that motor could be repaired in less expense and without other losses.

In the proposed work a comparative analysis is done so that a comparison between healthy and faulty rotor could be understood and a clear response of a healthy and faulty motor could be visualized to take decision that either motor is healthy or faulty and in case of fault; the level of fault could be recognized so that a rapid action could be taken at the time of severity. Proposed model shows the response of faulty motor in rotor bar broken case with one, three, five and eight bars. Generally for one broken rotor bar the motor is at initial phase of fault and could be repaired easily whereas for three and five broken bar of rotor immediate action should be taken and for eight or more than eight broken rotor bars the fault is at severe stage and a rapid response is needed which in case of delay would lead to the destruction of motor and in case of high power motor the motor and its surrounding is at fatal stage. There are certain other faults could be occurred in an induction motor in load and no-load case but the first attempt to minimize the negative outcomes of a faulty machine is to switch motor in no-load condition so that the fault could be recognized without damaging the motor and minimized negative effects of fault.

Motor's model is described in modeling section. A faulty motor and change in rotor resistance is described in the section after modeling then results are analyzed and compared.

II. Simplified Model of an Induction motor

A general model of a three phase induction motor is described with computer implementation [1] in SIMULINK is shown below in sub-model's form

The sub-model to implement three phase into two axes transformation (3/2) of stator voltages, currents calculation is shown in equation (1)

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$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \tag{1}$$

V_{as} V_{bs} V_{cs} are three phase stator voltages whereas, V_{ds} and V_{qs} is transformation of stator voltage in two axes transformation of vector V_s.

Currents equations of three phase induction motor in two axes stator reference frame is given in equation (2). Where, the values of inductance and resistance of rotor and stator and mutual inductance is kept constant where as they might be slightly change in real time motor mechanism.

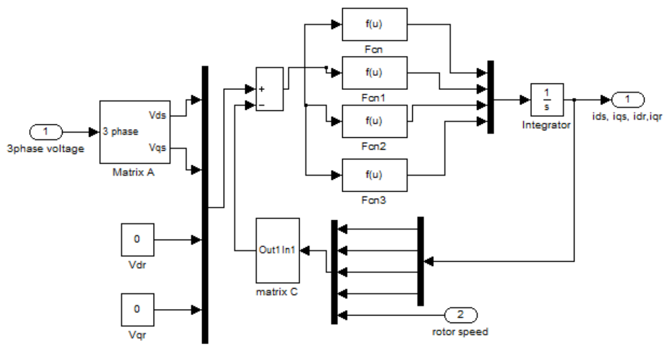

Fig. 1. Electrical model of an induction motor in SIMULINK

$$I = \int_{\tau=0}^{t} \{L^{-1} \times (V - R \times I)\} d\tau$$

Where,

$$I = \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix}, \mathrm{L} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}, \mathrm{V} = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix},$$

$$\mathrm{R} = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & \frac{P}{2}\omega_0 L_m & R_s & \frac{P}{2}\omega_0 L_r \\ -\frac{P}{2}\omega_0 L_m & 0 & -\frac{P}{2}\omega_0 L_r & R_r \end{bmatrix}$$

Implementation of equation (2) is such that the input is $[V_{as} \quad V_{bs} \quad V_{cs}]$ and $[i_{ds} \quad i_{qs} \quad i_{dr} \quad i_{qr}]$ are the output current of stator and rotor from the model shown in figure 2. Here, $V_{dr} = 0$ and $V_{qr} = 0$ due to the short circuited winding of cage rotor.

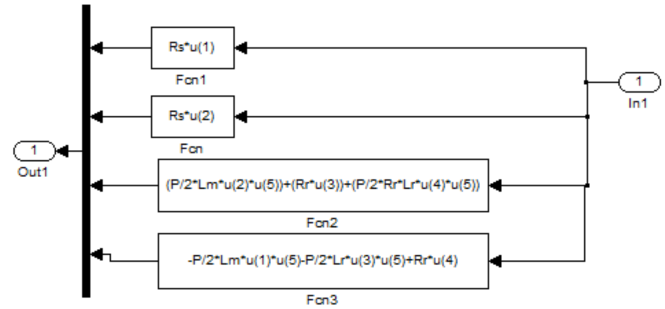

Fig. 2. Matrix 2 implementation using 'Fcn' block of MATLAB/SIMULINK

Torque sub-model of the motor is implemented using equation (3) and mechanical sub-model using equation(4)

$$T = \frac{PL_m}{3}\left(i_{dr} i_{qs} - i_{qr} i_{ds}\right) \tag{3}$$

$$\omega_0 = \int_{\tau=0}^{t} \frac{T - T_L}{J} d\tau \tag{4}$$

The torque and mechanical sub-model is implemented as shown in figure 3 and figure 4 respectively.

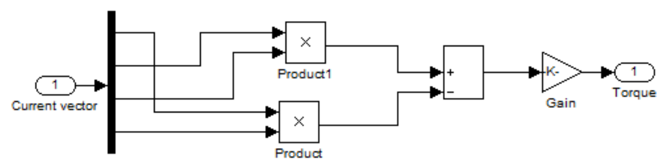

Fig. 3. Torque sub-model

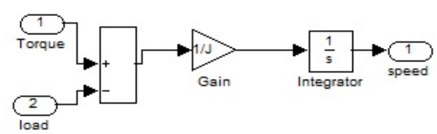

Fig. 4. Mechanical sub-model

Output sub-model of the stator current of three phase induction motor is calculated using equation (5) and could be implemented using 'Fcn' block of SIMULINK.

$$|i_s| = \frac{2}{3}\sqrt{\left(i_{ds}^e\right)^2 + \left(i_{qs}^e\right)^2} \tag{5}$$

The complete block diagram of three phase induction motor is using equations (1-5) is given in figure 5.

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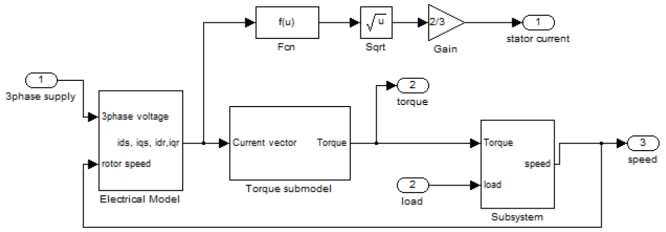

Fig. 5. Induction motor

A three phase sinusoidal voltage generation is achieved using equation (6) as |V| is the amplitude of the terminal voltage, Q is initial phase angle and w is the supply frequency

$$\begin{cases} V_{as} = |V| Cos\left(\omega t + \theta\right) \\ V_{bs} = |V| Cos\left(\omega t - \dfrac{2\pi}{3} + \theta\right) \\ V_{cs} = |V| Cos\left(\omega t + \dfrac{2\pi}{3} + \theta\right) \end{cases} \quad (6)$$

Three phase voltage model is shown in figure 6.

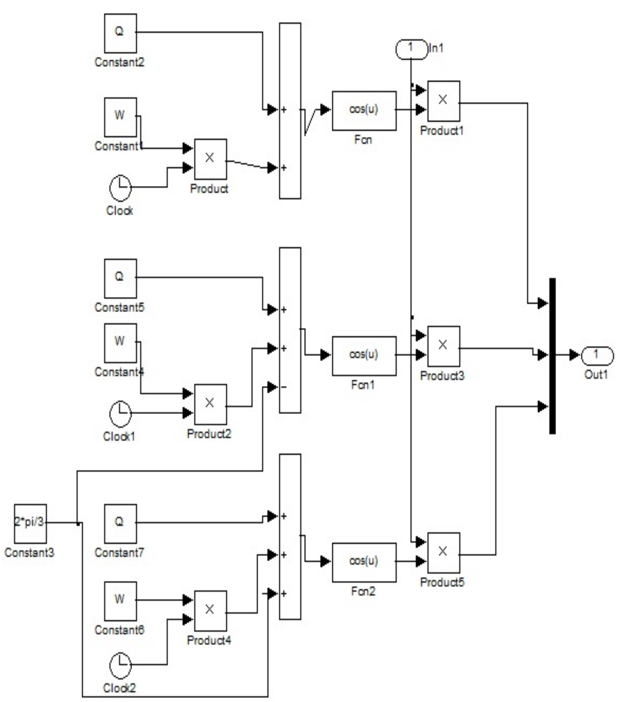

Fig. 6. Three phase supply sub-model

The terminal voltage is given by equation (7) due to the supply cable's voltage drop and it's implementation is shown in figure 7.

$$|V| = E - R_c |i_s| \quad (7)$$

Where E is supply voltage and R_c is cable resistance

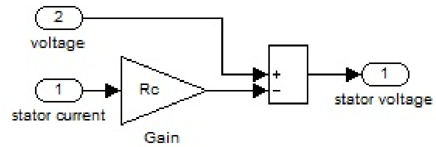

Fig. 7. Terminal voltage sub-model block

The complete presentation of power supply for a three phase induction model is shown in figure 8 using equation (6) and (7).

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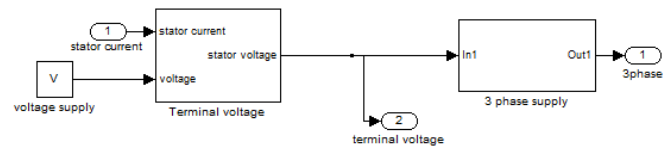


Fig. 8. Power supply sub-model

Using power supply sub-model and induction motor sub-model a complete representation of the system is implemented as shown in figure 9.

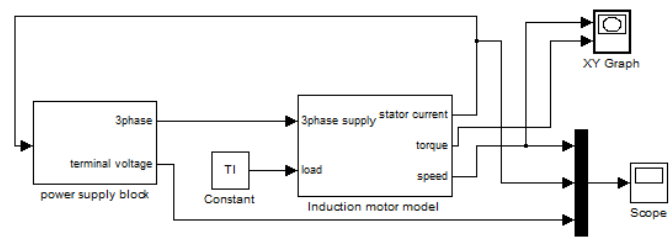


Fig. 9. Induction motor model

The XY-graph block is used to get the torque/speed characteristic of the three phase induction motor

III. Faulty Motor Analysis

Broken rotor bar faults occurred generally in induction motor due to different reasons some of them are thermal stress, magnetic tension, bearing failure, dynamic pressure and load variation [2], [3], [4]. The present work is a comparative analysis of a healthy and a faulty motor (broken rotor bar fault). Considering dynamic resistance of the rotor as its depending upon the number of bars broken. There are several methods and models to identify the resistance of broken rotor bar, we are considering one of the model[5] to identify the value of that changed resistance as the rotor broke and the value of that resistance is change as number of broken rotor bars change.

$$\Delta \mathrm{R} = \frac{n_b}{\frac{N}{3} - n_b} R_r \qquad (8)$$

In the equation above R_r is the rotor resistance when no bar is broken, N is the number of total bars in rotor, n_b is the number of rotor bars broken in rotor. This change in rotor resistance is used to simulate the model of healthy and faulty rotor of an induction machine.

IV. Simulation And Results

The induction motor chosen for the simulation studies has the following parameters:
Type: three-phase, 4-pole, wye-connected, squirrel-cage induction motor with,

R_s =0.088 Ω/ph R_r =0.187 Ω/ph

L_s =0.0425 Ω/ph L_m =0.04 Ω/ph

L_r =0.0425 Ω/ph J=0.4 kg m^2

J_L =0.4 kg m^2

The transient operation of the three phase induction motor is illustrated using the simulation study of direct-on-line starting. At t=0, the motor, previously de-energized and at standstill connected to a 460 V, 50 Hz three-phase power supply through a cable.

Motor's stator current reflects the overall condition of an induction motor by representing frequency parameters of that current signal. Thus, fault diagnosis by mean of stator current spectrum investigation[6] for a healthy and a faulty motor is done.

Since, in an induction motor mechanical angular speed of a rotor is less than the rotating electrical fiend of a stator. Therefore, the slip is always less than '1' in running condition.

$$\mathrm{S} = \frac{\omega_{sm} - \omega_{rm}}{\omega_{sm}} \qquad (9)$$

Frequency components that occurs in stator current spectrum with defective rotor bar forms twice slip frequency[7] which can be shown as

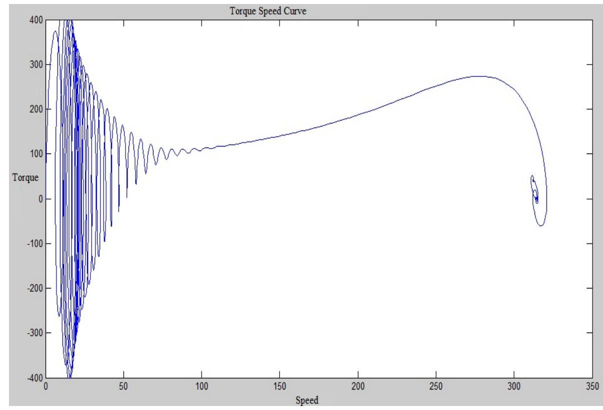
$$\mathrm{f}_{brb=} \left(1 \pm ks\right) f \qquad (10)$$

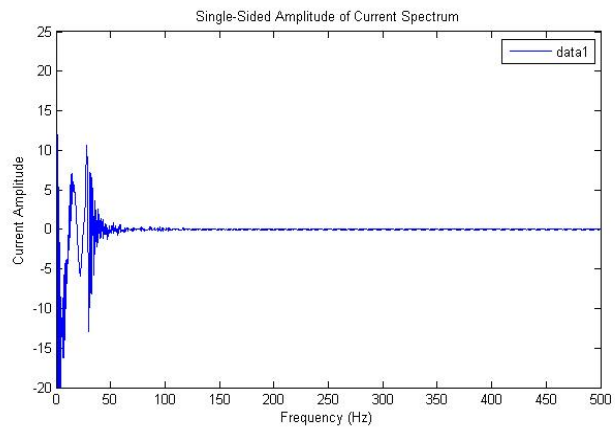
Where k=1,2,3,…. and 7

The additional frequency components and their amplitude describes the severity of fault. When the number of broken rotor bar is much smaller then total number of bars in a rotor or can say there is no broken rotor bar only (1$\pm$ 2s)f component will appear in spectrum of stator current.

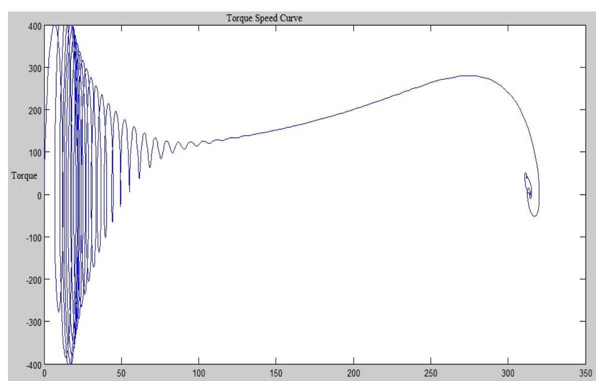
As fault become more severe there is an arise in higher order harmonics which is clearly understandable that rotor bar is defected and the number of defected bars can be estimated by analyzing the overall response of stator current spectrum. As the number of broken rotor bars increase, current's flow increases which in turn dissipated in the form of heat which is not only affecting the efficiency of motor but damages the winding as well.

Further, Torque-Speed curve is shown as a supportive parameter which is altering according to the number of broken rotor bar.





a- Healthy rotor.



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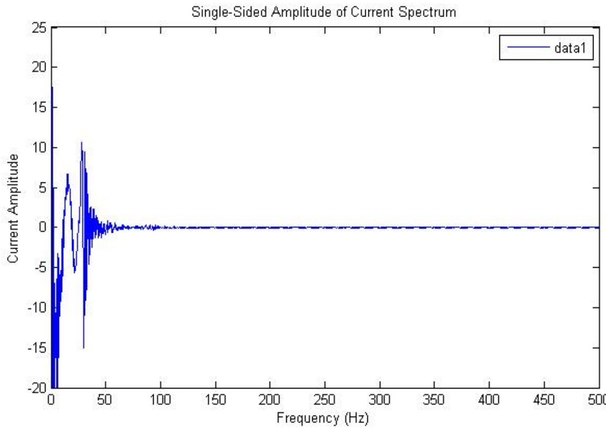
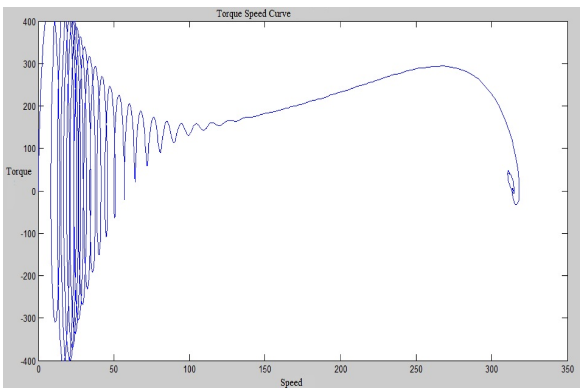
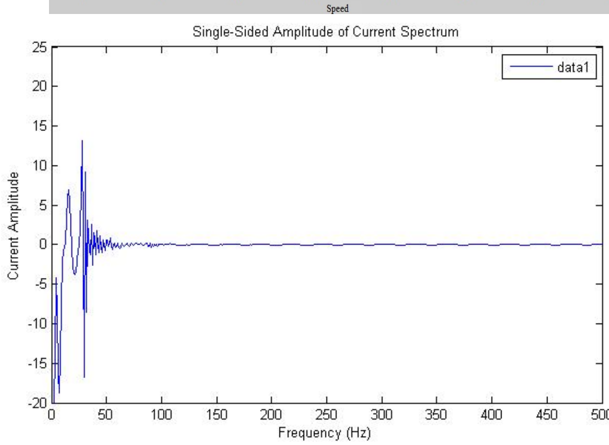
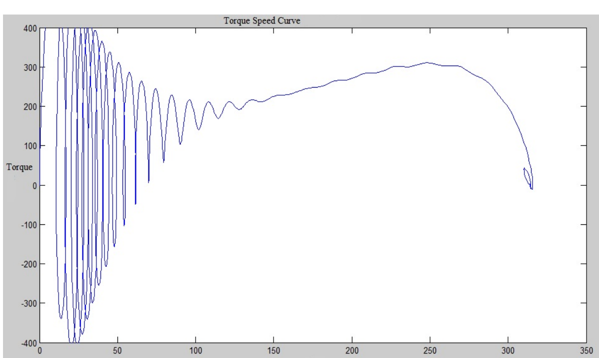


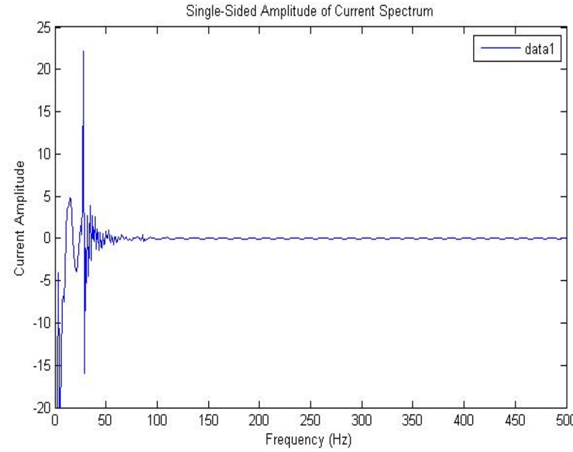
b- Rotor with 1 broken rotor's bar.



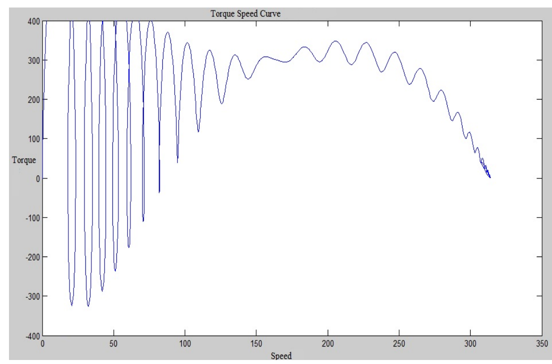


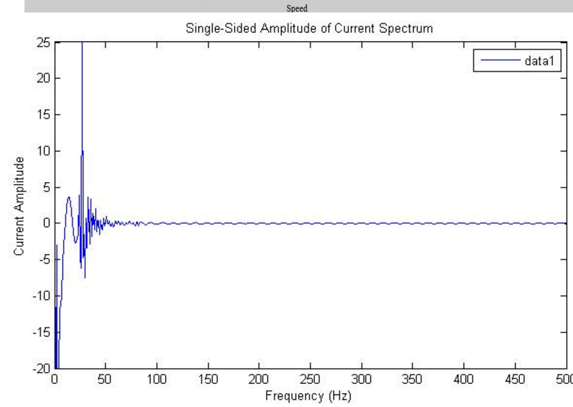
c- Rotor with 3 broken rotor's bars.





d- Rotor with 5 broken rotor's bars.





e- Rotor with 8 broken rotor's bars.

Fig. 10. current spectrum of healthy and faulty rotor bar

Current samples obtained from the model described above is used to identify the response and spectrum changes between healthy and faulty motor with one or more than one broken rotor bars. As shown in figures 10 the increase in number of broken rotor bar is increasing the spectral changes in the stator current spectrum. As the number of broken bar increase the speed-torque curve shows the effect on speed which is stabilizing with certain perturbations. Whereas, the current response or difference between rated and operational current can be observe to get the clear understanding of number of broken rotor bar.

comparing healthy motor with a faulty, we can understand that in a healthy motor speed-torque curve is showing smoothness as the rotor gets the speed of 110. Whereas, in a faulty motor of 8 broken rotor bars, the speed-torque curve is in continuous variation as can be visualized.

A detection index threshold is proposed by Kliman[8], claims that there is probably no fault if difference in amplitude between fundamental frequency and current sideband frequency component less than is 60dB and that for the difference which is greater than 50dB there is a broken rotor bar. Whereas, for the difference in amplitude between these two frequencies is at least 54dB there is a probably a cracked bar. So, that preventive measures could be taken.

V. CONCLUSION

It can concluded that the change in resistance of rotor which is in accordance with the number of rotor bar broken is translated in form of increased rotor resistance, we can analyze the number of broken rotor bar and can visualize the severity of the fault by mean of current consumption so that preventive maintenance measures could be taken which is comparatively easy for engineers than breakdown maintenance so that production and operation of an industry doesn't suffer.

Hardware implementation of the proposed method can be performed using an experimental setup so that live motor and its responses could be visualized to validate the authenticity of the working model and further improvement could be made, if possible.

REFERENCES

[1] K. L . SHI, T . F. CHAN, Y. K. WONG and S. L . HO "Modelling and simulation of the three-phase induction motor using Simulink", Int. J. Elect. Enging. Educ., Vol. 36, pp. 163–172, 1999.

[2] S. A. Taher and M. Malekpour, "A novel technique for rotor bar failure detection in single-cage induction motor using FEM and MATLAB/ SIMULINK," vol. 2011, pp. 1–14, 2011.

[3] Nandi and H. A. Toliyat, "Fault diagnosis of electrical machines-a review," in *Proc. Int. Electric Machines and Drives Conf*, pp. 219–221, 1999.

[4] Nandi and H. A. Toliyat, "Condition monitoring and fault diagnosis of electrical machines-A review," in *proc. Ind. Applicat. Soc*., vol. 1, pp. 197–204, 1999.

[5] A. Bellini, F. Filippetti, G. Franceschini, C. Tassoni, and G. Kliman, "Quantitative evaluation of induction motor broken bars by means of electrical signature analysis," Industry Applications, IEEE Transactions on, vol. 37, no. 5, pp. 1248–1255, 2001.

[6] M. E. H. Benbouzid, "A review of induction motors signature analysis as a medium for faults detection," *IEEE Trans. Ind. Electron*., vol. 47, pp.984-993, Oct. 2000.

[7] F. Filippetti, G. Franceschini, C. Tassoni, and P. Vas, "Ai techniques in induction machines diagnosis including the speed ripple effect," *IEEE Trans. Ind. Electron*., vol. 34, pp. 98-108, Jan./Feb. 1998.

[8] G. B. L\Kliman, R. A. Koegl, J. Stein, and R. D. Endicott, "Noninvasive detection of broken rotor bars in operating induction motors," *IEEE Trans. Energy Conversion,* vol. 3, pp. 873-879, Dec. 1988.