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ORIGINAL CONTRIBUTION

A Proposed Method for Detecting Broken Bar Location of Cylindrical Rotor in Asynchronous Motors Using Angle-Axis Rotation under Optimum Condition

Ujjal Dey*, Dilip Dey, Sourav Tola and Ayandeep Ganguly

Haldia Institute of Technology, Haldia, WB, India

Email: ujjaldey54@gmail.com, dilip_de@rediffmail.com, sourav_bec@gmail.com, gangulyayandeep@gmail.com

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ABSTRACT

In today's industries, Induction motors are extensively used and they are exposed to different hostile environments, manufacturing defects, etc. Various detection methods and computational techniques are practiced to detect incipient faults. Current signature analysis grabs the attention of researchers as an accurate and simple technique for motor fault diagnosis. In this proposed method, On-line early detection and diagnosis of rotor fault along with its location of occurrence is analyzed considering rotor current components. The increased in demand has greatly improved the approach of fault detection in poly phase induction motor. Artificial intelligence techniques have proved their ability in detection of incipient faults in electrical machines. With the development of pattern recognition and data mining, machine learning based methods have been a research focus gradually in the field of intelligent fault diagnosis.

KEYWORDS: Broken Bar fault, Sectionized Rotor, Angle axis rotation, MCSA

1. INTRODUCTION

REVIEW ABOUT MOTOR FAULTS

In the case of non-stationary conditions, speed variationsmust be distinguished from angular velocity perturbation caused by the presence ofa defect[1].The fault condition will ideally bedetected at an incipient stage which will potentially reduce those costs associated withunplanned breakdowns [2].

Induction motors are subjected to primary types of fault and related secondary faults. Condition monitoring and fault diagnostics are usually implemented by investigating the corresponding anomalies in machine current, voltage and leakage flux.Depending on the regionof fault occurrence, induction motor faults are mainly put under the following categories:

i) **Stator Faults:** Faults in the stator winding such as turn-to-turn, coil-to-coil, open circuit, phase-to-phase andcoil-to-ground[3]. Along with this, vibration and circulating currents in frame, core slackening and hotspots in laminations, winding faults in end winding portion are also venerable for motors.

ii) **Rotor Faults**: Such faults are developed due to bar defect or bar breakage. The torque affected considerably due to broken bars [4]. Faults due do long term load unbalance results to damage of bearings and non-uniform air gap.

iii) **Air gap Eccentricity Faults:** Static and dynamic air gap eccentricities occur due to unequal air gap between stator and rotor[5].Cause of dynamic eccentricity can

*Corresponding author: ujjaldey54@gmail.com

be a bent shaft, bearingwear and movement, or mechanical resonances at critical speeds and imperfect positioning of stator or rotor during commissioning phase or stator core ovality can cause static eccentricity.

iv) Other faults include bearing fault, drive shaft misalignment and vibrational faults under mechanical faults. Bearing fault is the major factor which causes about 40% of motor faults.

2. BRIEF SURVEY OF EARLIER RESEARCH WORKS

Condition monitoring applied to induction motors are based on different physical magnitudes such as vibration, stator currents, and sound signals. More than 82% of fault diagnosis methodologies have been done using vibration analysis [6-8] which is better suited for mechanical fault identification. Stator current based analysis has been also adopted by many researchers due to its advantages of being noninvasive and easy to use. In this regard, the fusion of both vibration and current analysis is expected to increase the multi-fault occurrence detection capabilities [9-12]. Very popular trend in recent past was to analyze motor current signatures[13-16], with the help of power spectrum density analysis[17], Fast Fourier Method[17], Wavelet Transform [18], neural or Fuzzy implementation[19-22], Hilbert Huang Transform (HHT) [23-25], space vector modulation[25,26] etc. Along with these analyzing tools, not much emphasis has been given to detect the actual location of fault occurring in rotor bars.

3. PROPOSED ANALYSIS BASED ON DYNAMIC MODEL OF MOTOR

The vector control algorithm is based on two fundamental ideas. The first is the flux and torque producing currents. An induction motor can be modeled most simply (and controlled most simply) using two quadrature currents rather than the familiar three phase currents actually applied to the motor. These two currents called direct (Id) and quadrature (Iq) are responsible for producing flux and torque respectively in the motor. By definition, the Iq current is in phase with the stator flux, and Id is at right angles. Of course, the actual voltages applied to the motor and the resulting currents are in the familiar three-phase system. The move between a stationary reference frame and a reference frame, which is rotating synchronous with the stator flux, becomes then the problem. This leads to the second fundamental idea behind vector control.

Implementing dynamic model of 3 phase Induction motor in MATLAB domain considering flux variations (Fig.1). Some of the governing equations are as follows:

Flux components:

$$\lambda_d^s = L_s i_d^s + L_m i_d^R$$

$$\lambda_q^s = L_s i_q^s + L_m i_q^R$$

$$\lambda_d^R = L_R i_d^R + L_m i_d^s$$

$$\lambda_q^R = L_R i_q^R + L_m i_q^s$$

Voltage Components:

$$V_d^s = R_s i_d^s + \frac{d}{dt}\lambda_d^s$$

$$V_q^s = R_s i_q^s + \frac{d}{dt}\lambda_q^s$$

$$0 = R_r i_d^R + \frac{d}{dt}\lambda_d^R + \omega\lambda_q^R$$

$$0 = R_r i_q^R + \frac{d}{dt}\lambda_q^R - \omega\lambda_d^R$$

Torque equation: $T = \lambda_q^R i_d^R - \lambda_d^R i_q^R$

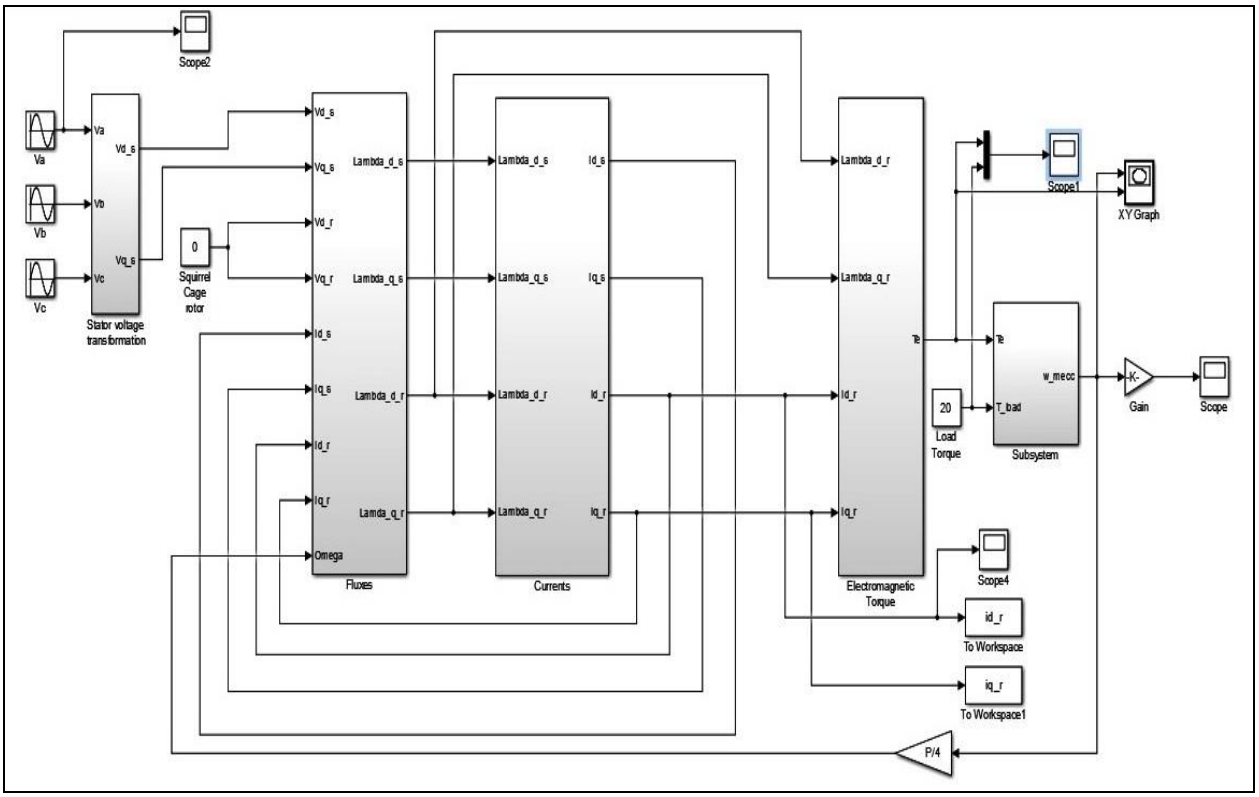


Figure 1: Simulation of d-q model of motor

Considering a 420V, 50 Hz motor configuration with appropriate values of stator and rotor parameters derived from power rating, the characteristics of healthy condition are obtained as follows (Figure2 to Figure5).

Under some assumptions, a squirrel-cage induction machine having 'k' consecutive broken bars behaves similarly to an equivalent slip-ring one having the same parameters but an electrically unbalanced rotor winding [6]. In particular, one of the three rotor phases shall include an additional resistance R_F whose value (referred to the stator)depends on the percentage of broken rotor bars

$$R_F = \frac{3k}{P-3k} R_r$$

Where R_r is the rotor resistance (referred to stator) in healthy condition while P represents the total number of rotor bars.

Without loss of generality, if the machine is transformed into an equivalent asymmetrical two-phase machine, the additional resistance R_F will appear in one of the phases. Let us consider that the fault is located along the d-axis of the rotor. In this case, the resistances of the two rotor windings will be

$$R_{rd} = R_r + R_F \text{ and } R_{rq} = R_r$$

Modifying these values in simulation, the broken bar fault can be reflected by following characteristics (Fig 6 to Fig 9) :

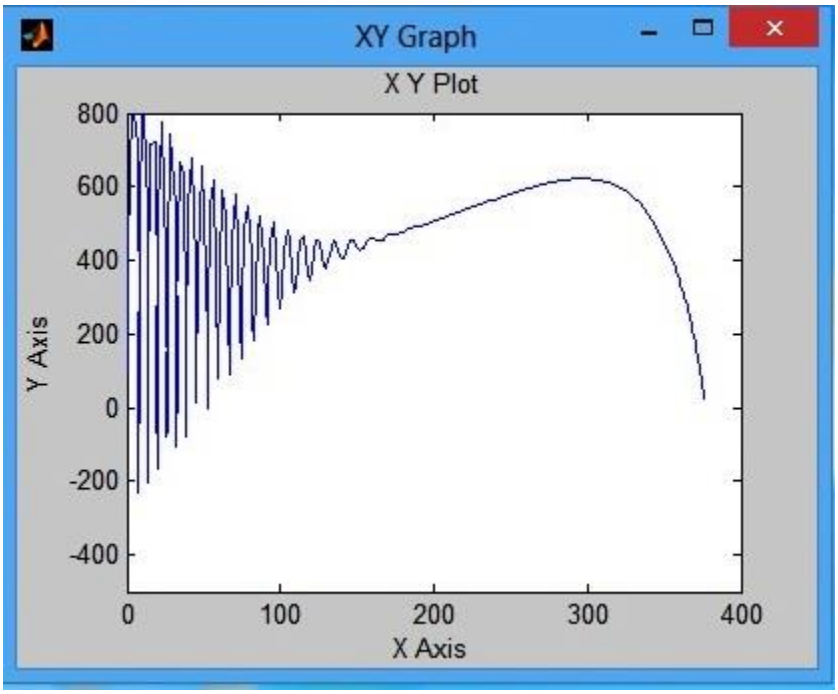


Figure 2: Torque- speed characteristics

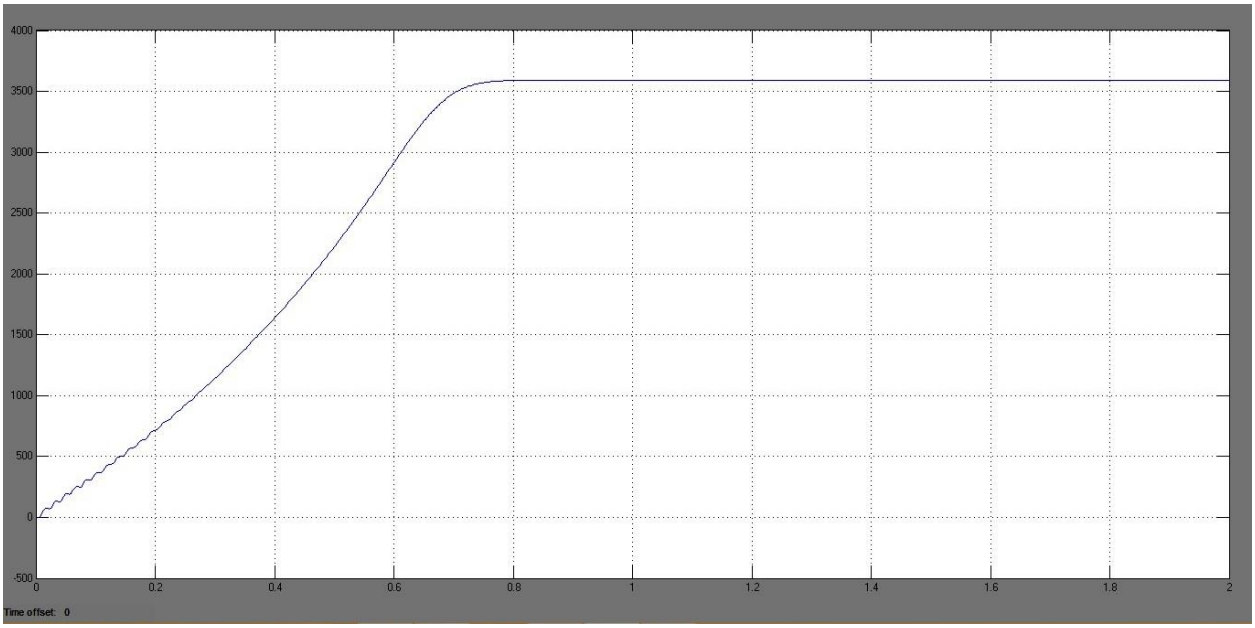


Figure 3: Speed-time Curve

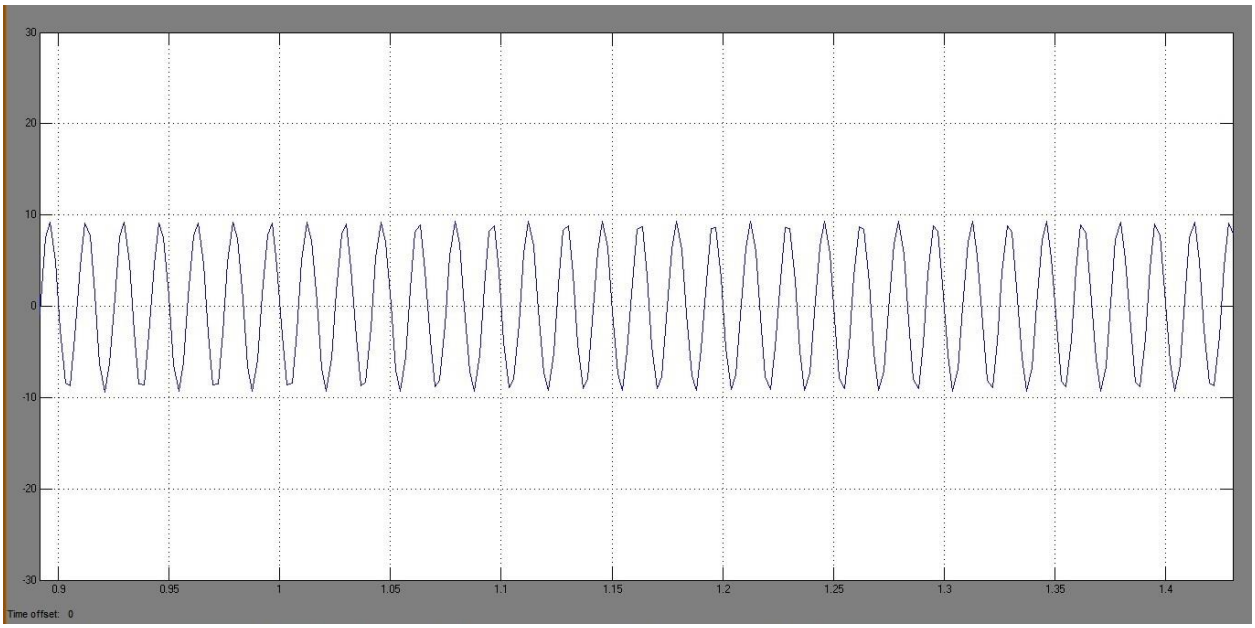


Figure 4: Direct axis current (Id_r)

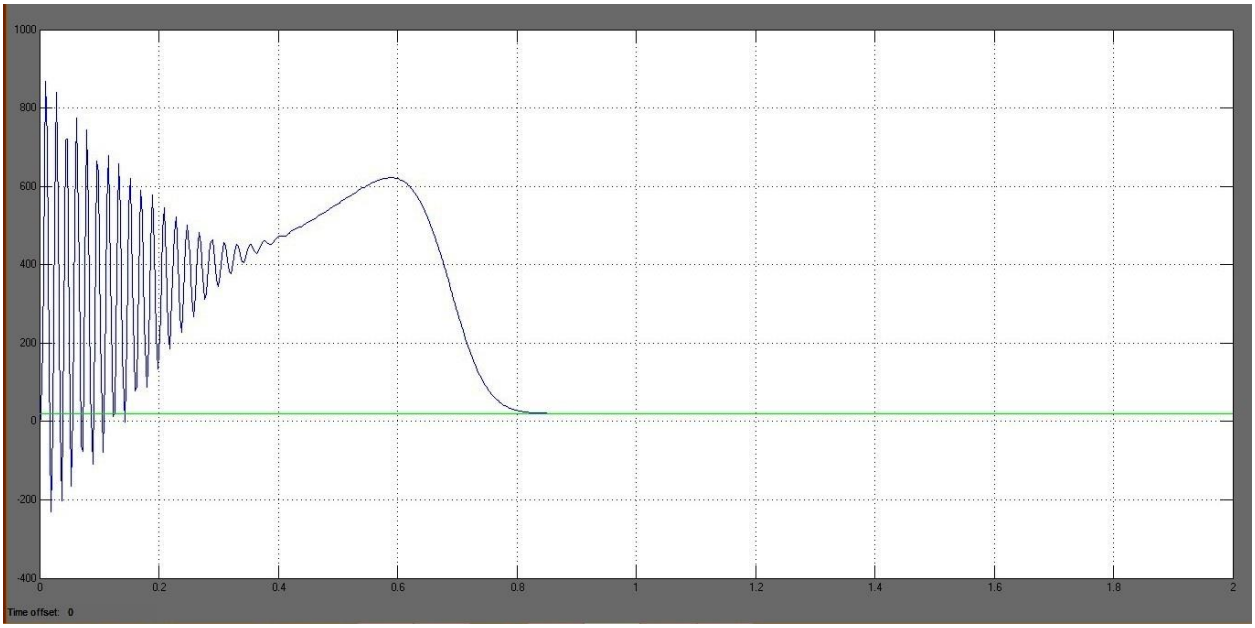


Figure 5: Motor Torque & Load Torque

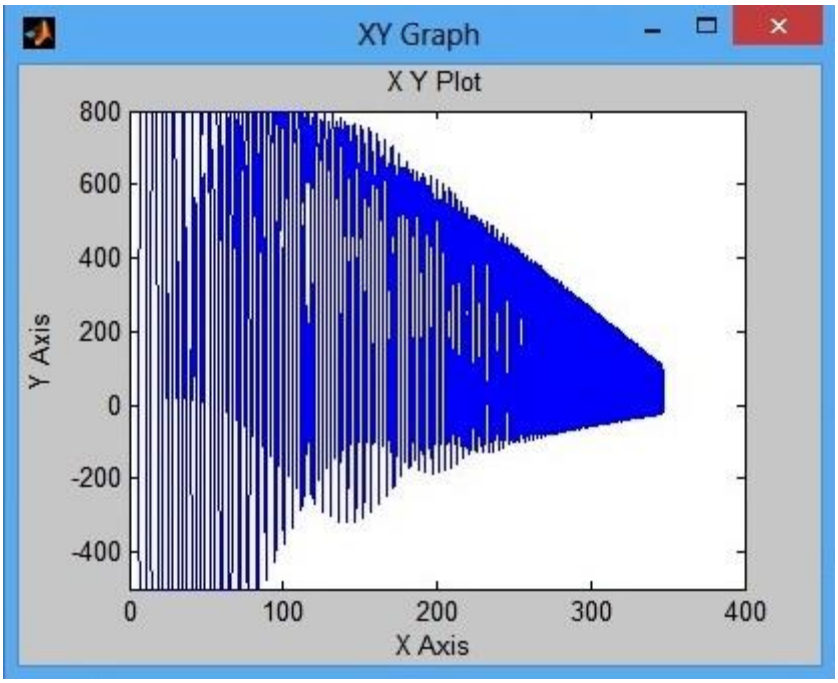


Figure 6: Torque- speed characteristics under Broken Bar

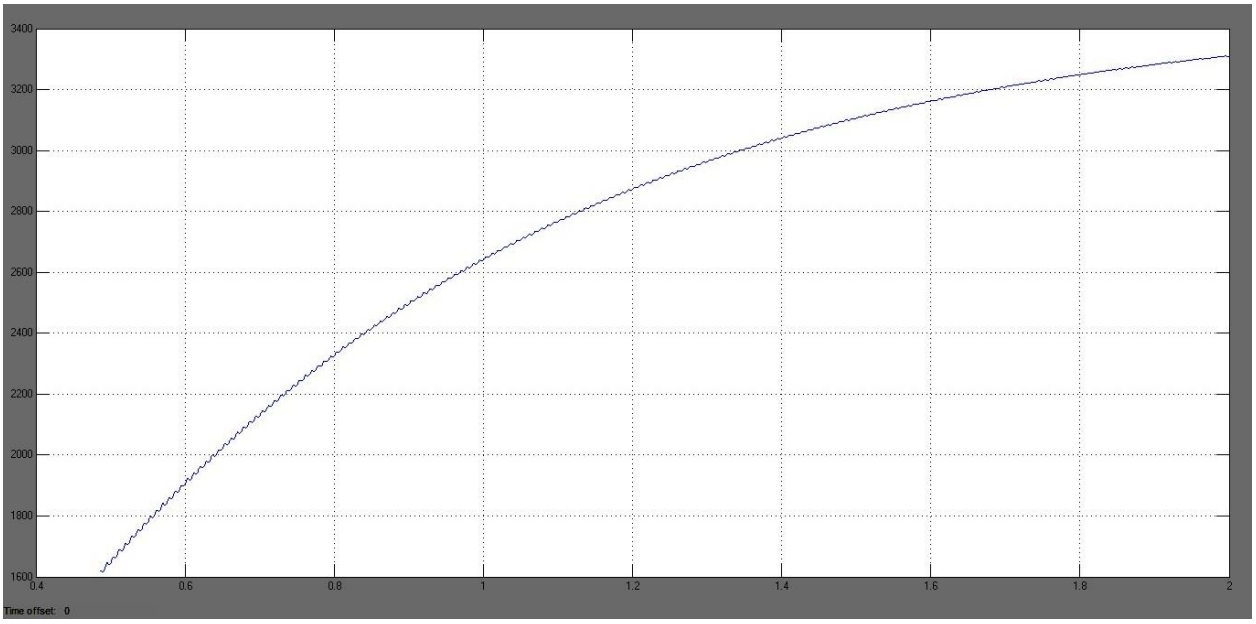


Figure7: Speed-time Curve under Broken Bar

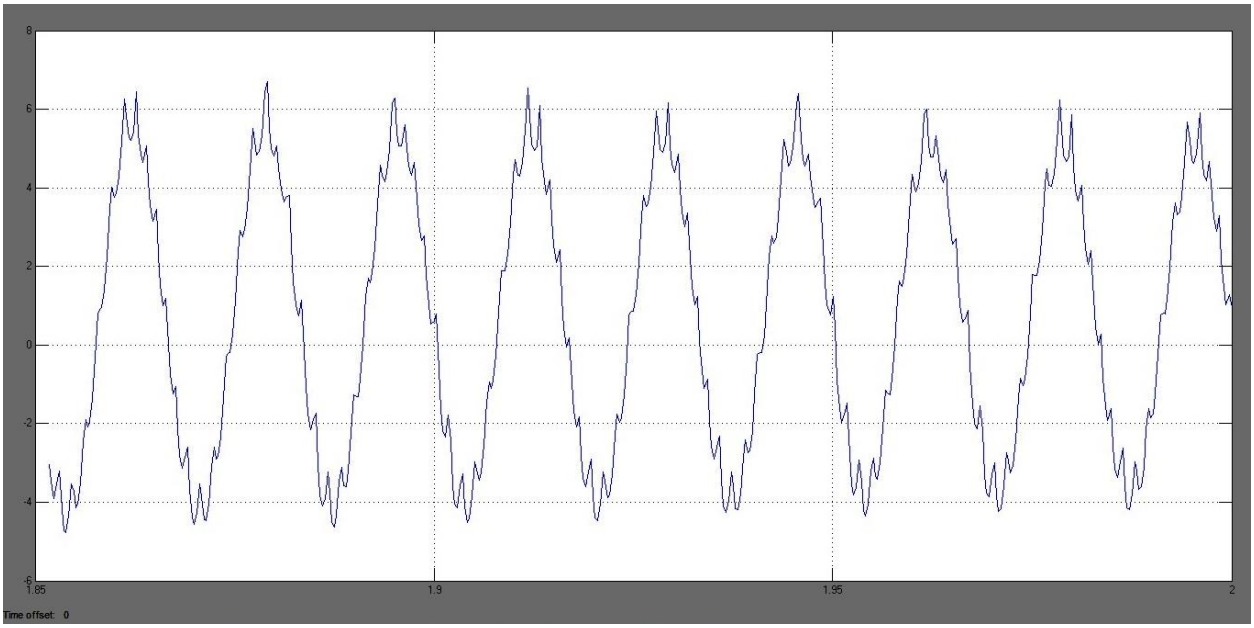


Figure 8: Direct axis current (Id_r) under Broken Bar

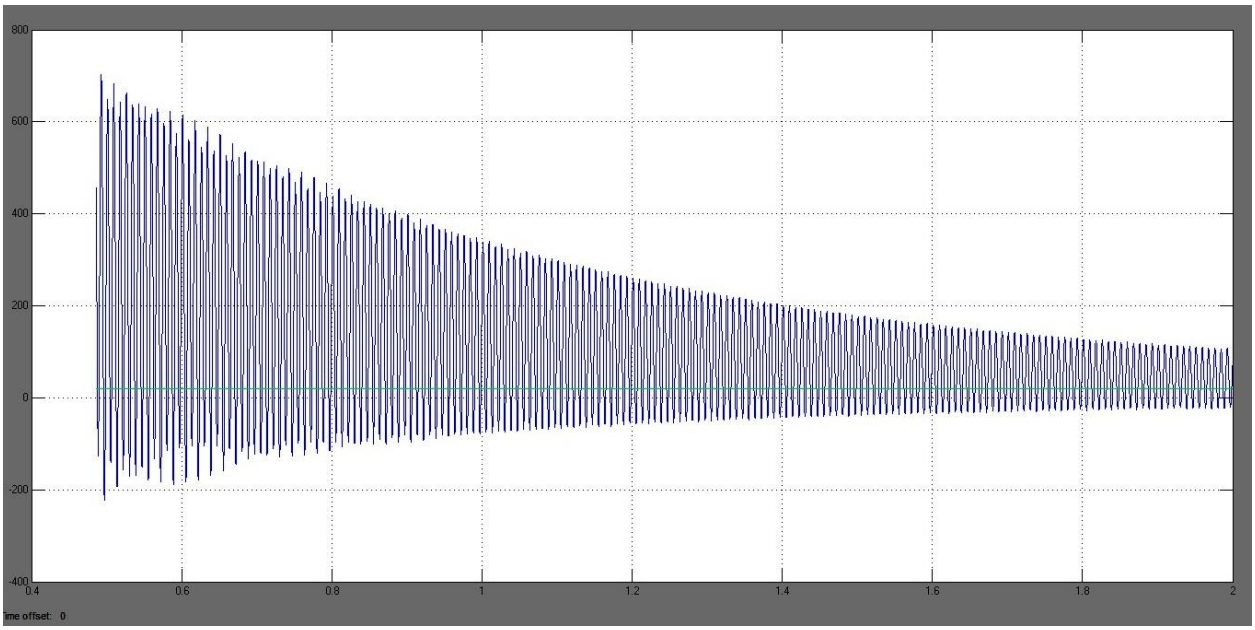


Figure 9: Motor Torque & Load Torque under Broken Bar

4. ROTOR FAULT LOCATION TRACKING UISNG ANGLE AXIS ROTATION

Current signatures are extracted from the simulation and placed in 3D curvilinear coordinates. In real time system, rotor currents are extracted from sectionized rotor.

The basic idea is to make the arbitrary rotation axis coincide with one of the coordinate axis. Specifying the coordinates (scalar components) of this basis in its current (rotated) position, in terms of the reference (non-rotated) coordinate axes, will completelydescribe the rotation. The axis (say z axis) can be represented as a three-

dimensional unit vector $\hat{e} = [e_x e_y e_z]^T$, and the angle by a scalar θ for a vector $\vec{v}$ to the final position $\vec{u}$. If the rotation angle is zero, the axis is not uniquely defined. Combining two successive rotations, each representedby an Euler axis and angle, is not straightforward, and in fact does not satisfy the law of vector addition, whichshows that finite rotations are not really vectors at all. Figure 10 describes generalized situation to apply angle axis rotation formula.

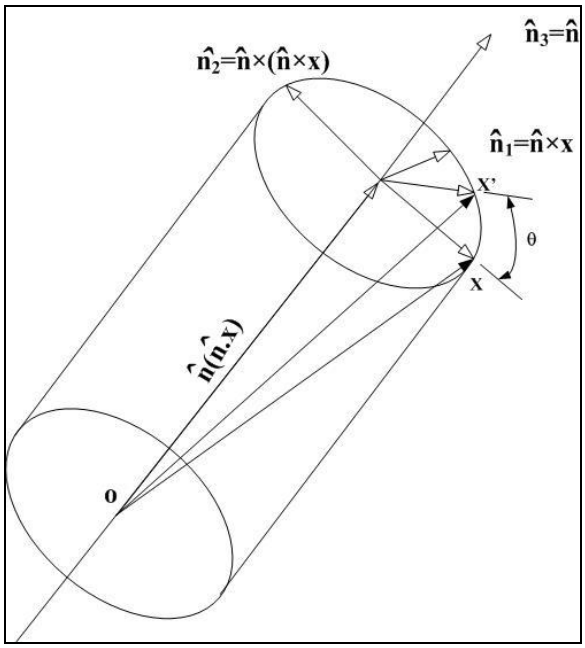


Figure 10: Angle axis rotation for any arbitrary vector x

It is best to employ the rotation matrix or quaternion notation, calculate the product, and then convert back to Euler axis and angle.

$$\vec{u} = \vec{v}\cos\theta + (\vec{k}.\vec{v})\vec{k}(1-\cos\theta) + (\vec{k}\times\vec{v})\sin\theta$$

with rotation vector

$$\vec{R} = I + [k]_x^2(1-\cos\theta) + [k]_x \sin\theta$$

$$[k]_x = \begin{pmatrix} 0 & -k_3 & k_2 \\ k_3 & 0 & -k_1 \\ -k_2 & k_1 & 0 \end{pmatrix}$$

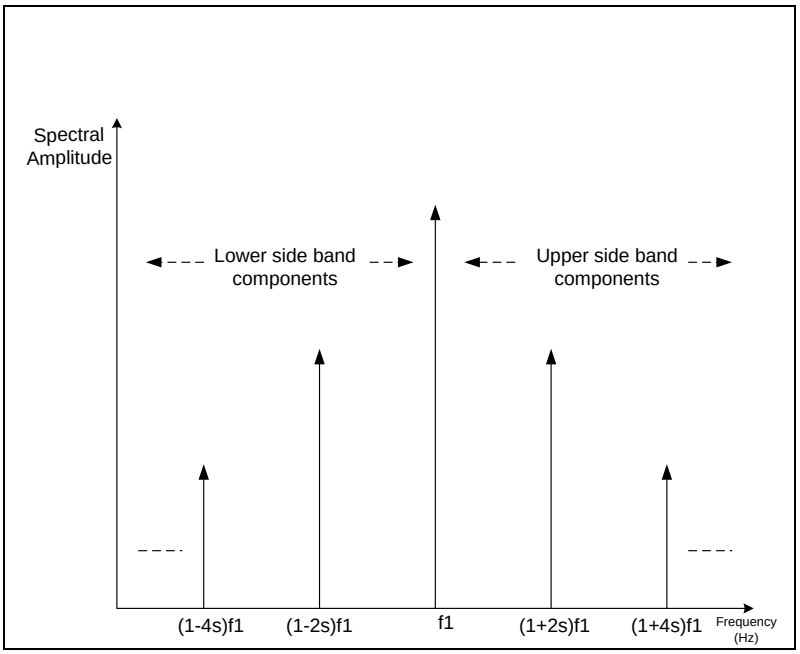
Expanding R , we can obtain the three-dimensional Rodrigues' rotation formula in the following form

$$R = \begin{bmatrix} \cos\theta + k_1^2(1-\cos\theta) & k_1k_2(1-\cos\theta) - k_3\sin\theta & k_1k_3(1-\cos\theta) + k_2\sin\theta \\ k_1k_2(1-\cos\theta) + k_3\sin\theta & \cos\theta + k_2^2(1-\cos\theta) & k_2k_3(1-\cos\theta) - k_1\sin\theta \\ k_3k_2(1-\cos\theta) - k_3\sin\theta & k_3k_2(1-\cos\theta) + k_1\sin\theta & \cos\theta + k_3^2(1-\cos\theta) \end{bmatrix}$$

Motor current signature analysis (MCSA) is the most popular method to detect rotor cage faults. This method performs frequency spectrum analysis of the stator currents to determine the

electromechanical conditions of the motor and the driven equipment. Broken rotor bar fault in induction motors can be detected by monitoring any abnormality of the motor current power spectrum amplitudes at several certain frequency components. In a squirrel cage induction motor with rotor asymmetry, the stator current spectrum will contain harmonic components I_1 at frequency $(1\text{-}2s)f_1$ and I_2 at frequency $(1+2s)f_1$. These components are dependent on different induction motor parameters and operating conditions, i.e. load and inertia. The broken bars also give rise to a sequence of other sidebands given by ,

$f_b = (1+2ks)f_1$, k=1,2,…,k_n which can be represented as,

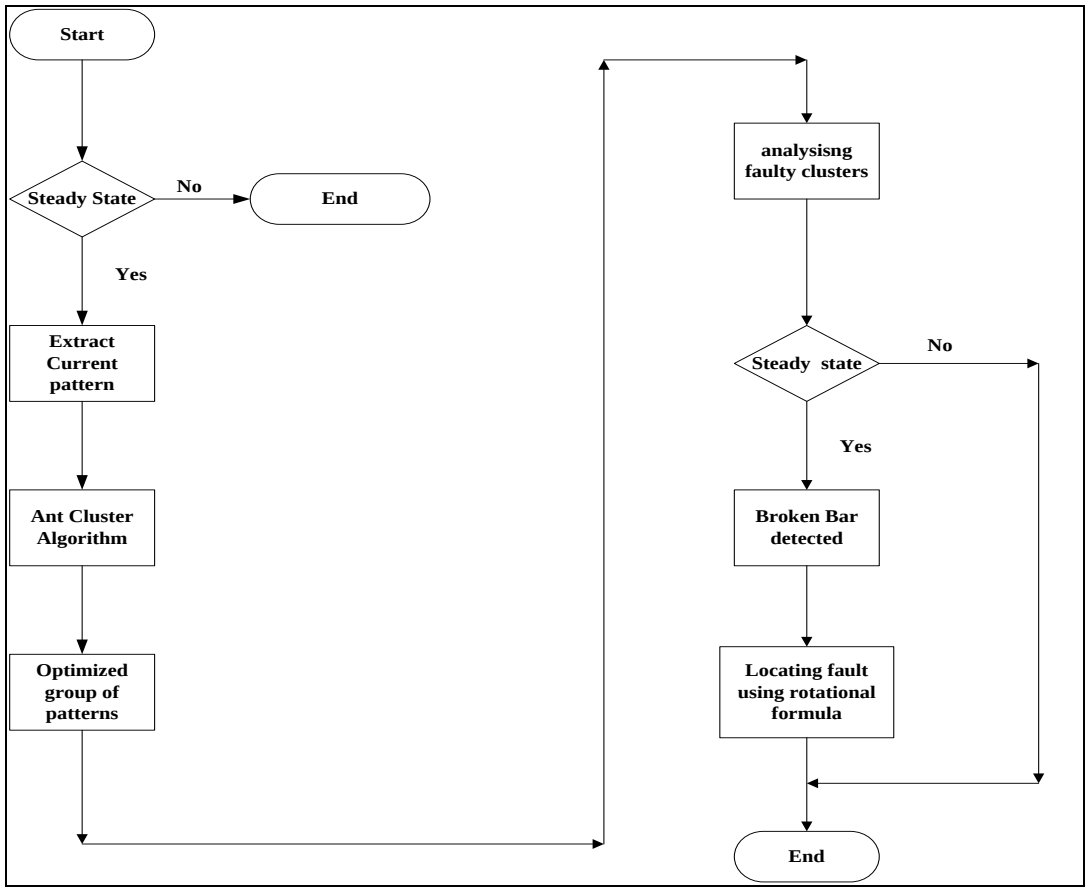


Eccentricity fault frequencies broken rotor bar fault frequencies and the fundamental component of thesupply are adjacent to each other.

The other frequency components observed under broken bar fault are given by

$$f_b = \left[\left(\frac{k}{p_p}\right)(1-s) \pm s\right] f_s \,,\ \frac{k}{p_p} = 1,3,5...$$

5. FLOWCHART OF PROPOSED METHODOLOGY:



6. ANT CLUSTER ALOGORITHM (ACA) FOR OPTIMIZATION:

The ant clustering algorithms are mainly based on versions proposed by Deneubourg, Lumer and Faieta. This proposed method uses an algorithm for data clustering, in which a set of concurrent distributed agents collectively discover a sensible organization of objects for a given dataset [27].The process of cluster analysis of motor currents consists of three important steps: Current feature extraction under healthy and faulty condition, similarity computation based on obtained features and grouping(clustering). In this first phase main features of currents are established along with method of comparison. The next stage shows the similarity between the currents take into consideration in term of thesechosen features, attributes. The result of similarity or dissimilarity computation is presented in the next step: grouping, the form of partitioning these objects into groups.

For an ant situated at grid cell ‘c’ and carrying a data item ‘k’, it uses its memory to proceed to all remembered positions, one after the other. Each of them is evaluated using the neighborhood function f*(k) for finding a dropping site for the currently carried data item K.

Threshold formula for picking and dropping decisions is:

$$c^{*}_{pick}(k) = 1, if \quad f^{*}(k) > 1$$

$$= \frac{1}{f^*(k)^2}, \text{ else}$$

$$c^*_{drop}(k) = 1, if \quad f^*(k) \geq 1$$

$$= \frac{1}{f^*(k)^4}, \text{ else}$$

Where, f*(k) is a modified version of Lumer and Faieta's neighborhood function:

$$f^*(k) = \frac{1}{\sigma^2}\sum_j \left[1 - \frac{d(i,j)}{\alpha}\right], \text{ if f*(i)>0 and } \left[1 - \frac{d(i,j)}{\alpha}\right] > 0$$

$$= 0, \text{ otherwise}$$

$\frac{1}{\sigma^2}$: a neighborhood scaling parameter,

α : a parameter scaling the dissimilarities within the neighborhood function f*(k),

d(i,j): a dissimilarity function.

Ant-based clustering algorithm requires a number of different parameters to be set, which have been experimentally observed. Parameters of this algorithm we can divide into two groups:
1. To be independent of the data,
2. To be set as a function of the size of the data set.
The first group includes:
• The number of agents, which be set to be 10,
• The size of the agents' short–term memory, which we equally set to 10,
• The initial clustering phase (from tstart to tend: tstart = 0.45·N , tend = 0.55·N, where N denote the number of iterations.

The generalized algorithm is consists of the steps presented below when given a set of un-ordered input patterns Z resulting coordinate represented by the height'h' and width'w'of the grid to generate a new location that is guaranteed to be on the grid,

1. Initialize a grid of size h×w , where h.w≥2|Z|
2. Randomly scatter patterns Z across the grid
3. Initialize 'm' ants in random locations
4. While stopping condition is not true for each ant : Move to new location
5. If the location contains a pattern :

    If the ant is not already carrying a pattern :

        Assign p←P(pick)
        Assign r←random()
        If r<p:
            Pick up the pattern
        Else if location contains no pattern

    If the ant is carrying a pattern:

```
Assign p←P(drop)
Assign r←random()
If r<p:
        Drop the pattern
```

7. CONCLUSION

A review of the most frequent IM failures and their detections via the MCSA is presented in this paper. Initially, the phenomenon of asymmetrical rotor is presented and all the characteristic frequencies occurring in the stator current of IM due to cracked or broken bars are explained. Also proposed method doesn't require advanced measuring equipment; only a current sensor is used for sampling one phase of stator current. Stator current frequency spectrum around fundamental component of the current was used to precisely diagnose the fault and location of the broken bars. Implementing the rotation formula for broken bars under running condition, will further be verified in a physical machine to check consistency.

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