Various Indices for Diagnosis of Air-gap Eccentricity Fault in Induction Motor-A Review

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Abstract. From the past few years, research has gained an ardent pace in the field of fault detection and diagnosis in induction motors. In the current scenario, software is being introduced with diagnostic features to improve stability and reliability in fault diagnostic techniques. Human involvement in decision making for fault detection is slowly being replaced by Artificial Intelligence techniques. In this paper, a brief introduction of eccentricity fault is presented along with their causes and effects on the health of induction motors. Various indices used to detect eccentricity are being introduced along with their boundary conditions and their future scope of research. At last, merits and demerits of all indices are discussed and a comparison is made between them.

1. Introduction
Because of its simple construction and cheap maintenance and repair, the induction motor is the most commonly used motor in the industry. Since induction motors are used very frequently, their protection and fault diagnosis schemes were developed along with their invention [1]. At that time schemes like overvoltage, ground fault and overcurrent protection were only applied. But now day’s scenario has been completely changed. Now, induction motors are exclusively used for severe process dynamics and control process and any fault in the motor will result in shut down of the whole process. So, in order to prevent huge financial loss, it is mandatory to have a trustworthy fault detection and diagnosis system for early detection of incipient fault.

There are basically electrical and mechanical faults in induction motors, of which 60% are mechanical faults and 80% of mechanical faults results in air-gap eccentricity [2], [3]. There are basically three types of eccentricity i.e. static, dynamic or mixed eccentricity.

2. Air gap eccentricity fault
There are basically three axes i.e. rotor symmetry axis O_r, stator symmetry axis O_s and rotor rotation axis O_w in an induction motor which coincides with each other in ideal condition. If eccentricity exists then there is a dislocation of any of the axis from the other two axes or dislocation of all the axes [4]. Eccentricity results in the unequal air-gap length along the stator to rotor circumference. This unequal air-gap length may either be static or dynamic depending upon the type of eccentricity. If stator symmetry axis O_s separates from the other two axes, the minimum/maximum air gap length is static and is called as static eccentricity. If rotor symmetry axis O_r separates from the other two axes and the minimum/maximum air gap length is dynamically moving then it is dynamic eccentricity. If all the three axes separate then it is mixed eccentricity. Three types of eccentricity are shown in (Fig. 1).
Fig. 1. Different eccentricity types: (a) static, (b) dynamic and (c) mixed

The reasons which cause eccentricity are described as follow [5]–[7]:

i. Operation of the motor at critical speed.
ii. Wrong positioning of rotor and stator at the time of manufacturing.
iii. Mechanical resonance at critical load.
iv. Oval inner cross section of the stator.
v. Wrong positioning of load axes and the rotor shaft.
vi. Wear and tear of ball bearings.

There is a generation of radial Unbalanced Magnetic Pull (UMP) between rotor and stator due to eccentricity which amplifies the degree of eccentricity within the motor. An enormous amount of burden is created on the machine which causes the wear and tear of the ball bearings. Also, the undesirable vibrations are produced in the stator windings due to radial magnetic forces caused by eccentricity. The worst happens when eccentricity causes rotor to stator rub which permanently damages stator core and rotor cage [6], [8].

Here are some adverse effects on the characteristics of the motor due to eccentricity:

i. Power losses increase, due to which efficiency decreases.
ii. The temperature of the windings increases.
iii. Overall average torque decreases.
iv. Variations in speed and torque increases.

Any change from the normal operation of the motor which can be measured can act as fault index for detection and diagnosis of faults. An ideal index can give results in all possible conditions. But sometimes it may happen that we are measuring a change in an index or a physical quantity due to the simultaneous existence of two or more faults. At that time, we require such an index which shows changes due to a fault and remains unchanged due to another fault.

This will help us in separately diagnosing simultaneously existing two or more faults. Different indices require different sensors and transducers for measurement. Therefore a comparison can also be made between indices on the basis of easiness of measurement, how precisely they detect and diagnose the fault, how the index behaves when there are fluctuating load conditions, machine gets magnetically saturated, voltage variations and voltage unbalance condition.

The main aim of this paper is to make a comparison between different fault indices in order to provide the researcher with complete information about which index will be best suited for the prevailing conditions and setup of the experiment.

3. Various indices used for detection of eccentricity

3.1. Normalized splitting severity factor (NSS)

For an induction motor with 4 poles, with the rotating magnetic field’s one complete rotation, two stator current cycles are produced. Rotating magnetic field encounters with unequal air-gap with the existence of static eccentricity within the motor. Due to magnetic reluctance, the different amplitudes of current will be produced as compared to the ideal or healthy motor. If park transformation over a complete rotation of stator current is drawn, it can be seen that there is a difference between two
current cycles if eccentricity fault exists in the motor. This difference can be used to detect the static eccentricity fault. The above mentioned index will be used for this objective.

If total P samples are received for two subsequent cycles of current and park’s current idn and iqn are found for P= 1, 2..n then normalized splitting severity factor will be given by:

\[
(\Delta \rho)_{avg} = \frac{(\Delta \rho)_{avg}}{\rho_{avg}}
\]  

(1)

Where the numerator of equation (1) is the difference of park’s current for two successive cycles and is given by:

\[
(\Delta \rho)_{avg} = \frac{\sum_{P=1}^{n} (\sqrt{i_{dn}^2+i_{qn}^2} - \sqrt{i_{dn/2+k}^2+i_{qn/2+k}^2})}{\rho/2}
\]  

(2)

And the denominator of (1) is the park’s current’s average length given by:

\[
\rho_{avg} = \frac{\sum_{P=1}^{n} \sqrt{i_{dn}^2+i_{qn}^2}}{\rho}
\]  

(3)

Using this technique the static eccentricity will only be eliminated if and only if the degree of eccentricity is above 60% but this method has an edge on others as it is simply measurable [9]-[11].

3.2. Difference of area under Park’s vector current for two consecutive current cycles to the average of all the areas (APC) [12]-[14]

For a 4-pole eccentric induction motor, if the magnitude of Park’s vector of current is plotted for two subsequent cycles against its angle from zero to 2π in electrical radians, then two different curves are obtained. If the difference of average area of two given curves and the sum of area of two curves is calculated then it can be used as an index for detection and diagnosis of eccentricity fault. Research can be further expanded to detect the dynamic and mixed eccentricity. Also, the effect of the variations in loading conditions and magnetic saturation can be determined.

3.3. High-frequency component of stator current (HFS) [15]–[21]

Harmonic components in the stator current of an eccentric induction motor are given by the following equation:

\[
f_{e} = f_{1} \left[ (kR \pm n_{d}) \frac{1-s}{p} \pm \theta \right]
\]  

(4)

where the power supply’s time harmonic order of the motor is \( \theta \), \( k \) is an arbitrary integer, \( P \) is the number of pole pairs, \( s \) is the slip, \( f_{1} \) is the fundamental component of supply frequency, \( R \) is rotor slot number, \( n_{d} \) is the degree of dynamic eccentricity given by 1, 2, 3,… and is zero for static eccentricity. These harmonic components will only be produced if it is not the third multiple of fundamental frequency i.e. 3\( (f_{1}) \) and also there exists a special relation between rotor slots and pole number [17]. There is a well set technique to detect the given harmonics. Firstly the stator current signal should be sampled with a particular frequency which satisfies the nyquist criterion. Now these sampled signals are passed through a specified filter in order to make the amplitude of the proposed harmonics visible. Since the amplitude of these harmonics is very low as compared to fundamental component it is mandatory to apply the filter. Now the required harmonic components are determined by applying Fast
Fourier Transform (FFT) to the filtered signal. This index can be well used for detection of fault as it does not show the changes when there is an unbalance in the voltage. Also it is precise and certain in making a difference between static and dynamic fault.

3.4. Low-frequency components of stator current (LFS) [22]–[27]
There is a drawback of the third index i.e. as it is based on high-frequency components noise signals also interfere highly with the main signal. To detect and to separate these signals is not so easy and requires very expensive hardware and software setup. Therefore such an index is required which is based on low-frequency components. It is found that following harmonic components of stator current exists in a motor with mixed eccentricity:

\[ f_e = |f_1 \pm kf_r| \] (5)

where \( f_1 \) is the fundamental frequency component of the supply, \( f_r \) is the frequency of rotor rotation in rotation per second (rps) and \( k \) is any random integer. The fundamental component of supply is surrounded with two harmonic components around it with \( k = 1 \). These two harmonics can be used as an eccentricity fault index for detection of fault. Unlike HS it is independent of the number of rotor slots and motor’s number of poles. But it depends upon the presence of mixed eccentricity within the machine. It has an advantage of comparatively easy computation and measurement. But till now the effect of unbalanced voltage, fluctuating load, magnetic saturation has not been found out and can be considered for further experimentation.

3.5. Stator current’s low and high frequency component (SLH) [28]–[33]
Both the low and high-frequency components must be found out and analyzed carefully in order to get more accurate results for mixed eccentricity. In reality low and high-frequency components are interconnected as due to the presence of both dynamic and static eccentricity stator current’s low-frequency components given by (5) also create some high-frequency components given by (4). Therefore in order to get more explicit results for mixed eccentricity both high and low frequency must be detected and analyzed. The motor’s number of poles and fluctuating load conditions does not effect the given fault index which makes it advantageous. But the effect of magnetic saturation is yet to be found.

3.6. Ratio of summation of low-frequency stator current components and no-load current of motor (RSN)
As stated in the fourth index, if the machine has mixed eccentricity fault then it will generate low-frequency components around the fundamental stator current frequency which are given by:

\[ f_e = |f_1 \pm kf_r| \] (6)
as similar to (5). Taking the value as 1 in an induction motor having 4 poles, the resultant frequencies will come out to be approximately near to 0.5\( f_1 \) and 1.5\( f_1 \) named as \( f_{eh} \) and \( f_{el} \) respectively. If the fault index is given by

\[ FI = \frac{f_{el} + f_{eh}}{I_{nl}} \times 100 \] (7)

where \( FI \) is fault index and \( I_{nl} \) is no load current. While going through [34] it has been found that the value of \( FI \) comes out to be 3.8% for a healthy motor. This is due to naturally or inherently existing static and dynamic eccentricity with in the motor. But if there is an introduction of 67% static eccentricity in the machine then the value of \( FI \) comes out to be 10.51%. Therefore it can be well used as an index to detect eccentricity fault in the motor. It has some other advantages of not affected by
fluctuations in load and unbalance in voltage. But the effect of magnetic saturation of motor should be further investigated.

### 3.7. Gyration radius of the torque developed (GRT)

The measurement of the developed torque is not an easy task as some special types of sensors are to be applied to the motor case which makes it difficult and expensive. It can be used as an index because stator current can be used as a replacement for it [35], [36]. If sampling is applied over the developed torque signals for a complete cycle and total N samples are gathered then for the first torque difference the time series is given by:

$$\Delta T = \{\Delta \tau(k), \ k = 2, 3, ... N\}$$  \hspace{1cm} (8)

where $\Delta \tau(k) = \tau(k) - \tau(k - 1)$ and $k$ is the number of torque samples. If a 2D phase space diagram is made with $\Delta \tau(k)$ on the vertical axes and $\Delta \tau(k - 1)$ on the horizontal where and is the number of torque samples. If a 2D phase space diagram is made with on the vertical axes and on the horizontal axes, it will show a considerable difference for eccentric motor as compared to healthy induction motor. Therefore it can definitely be used as an eccentricity fault index. On the 2D diagram, for a unit mass at any point, the mass center lies on the coordinates $\mu_0$ and $\mu_1$ for the total diagram. These $\mu_0$ and $\mu_1$ are given by:

$$\mu_0 = \frac{\sum_{k=1}^{N-l} \Delta \tau(k)}{N-l}$$  \hspace{1cm} (9)

$$\mu_1 = \frac{\sum_{k=l+1}^{N} \Delta \tau(k)}{N-l}$$  \hspace{1cm} (10)

The total distance between the mass center and any point is given by $d(k)$ as:

$$d(k)^2 = [\Delta \tau(k) - \mu_0]^2 + [\Delta \tau(k-1) - \mu_1]^2$$  \hspace{1cm} (11)

And, finally, the gyration radius is given by:

$$r = \sqrt{\frac{\sum_{k=1+l}^{N} d(k)^2}{N-l}}$$  \hspace{1cm} (12)

Around the mass center, there will be less concentration of the 2D diagram if the gyration radius is large which makes it able to be used as one of the index for eccentricity fault diagnosis.

### 4. Comparison of all the indices

An index is called as perfect if it helps us to identify different types of faults under different operating conditions. But in the real world, it is approximately impossible to have all the qualities in a single index. The reliability and feasibility of an index depends on various factors. It has been found from the literature review that deviations in voltage, levels of loading, unbalanced voltage, and magnetic saturation are some of the factors, which if altered affects the index value. Moreover factors like easiness in making calculations and measurements, precision in diagnosing fault intensity and type are some of the factors which decides the quality of an index. In the given Table 1 and Table 2 a comparison is made between all the indices for the manufacturers and researchers which will help them proceed further in their respective areas. Here the tick sign (✓) shows that the given index is affected, the cross sign (✗) indicates its contrast and the asterisk sign (*) indicates that the attitude of the index is not known towards the following weakness and is still under consideration for the future experimental scope of work.
Table 1. The behaviour of different indices corresponding to the following variations

| Index number | Magnetic saturation | Voltage deviation | Voltage unbalance | Load level |
|--------------|---------------------|-------------------|-------------------|------------|
| NSS          | *                   | *                 | *                 | *          |
| APC          | *                   | *                 | *                 | *          |
| HFS          | ✓                   | ✓                 | ✓                 | ✓          |
| LFS          | ✓                   | ✓                 | ✓                 | ✓          |
| SLH          | ✓                   | ✓                 | ✓                 | ✓          |
| RSN          | ✓                   | ✓                 | ✓                 | ✓          |
| GRT          | ✓                   | ✓                 | ✓                 | ✓          |

Table 2. The behaviour of Indices in front of their merits

| Index number | Precision and certainty in diagnosis of the fault type | Simplicity of measurement and calculation | Precision and certainty in diagnosis of the fault intensity |
|--------------|-------------------------------------------------------|------------------------------------------|----------------------------------------------------------|
| NSS          | ×                                                     | ✓                                        | ×                                                        |
| APC          | ×                                                     | ✓                                        | ×                                                        |
| HFS          | ✓                                                     | ×                                        | ×                                                        |
| LFS          | ×                                                     | ✓                                        | ×                                                        |
| SLH          | ×                                                     | ✓                                        | ×                                                        |
| RSN          | ×                                                     | ✓                                        | ×                                                        |
| GRT          | ✓                                                     | ✓                                        | ✓                                                        |

From Table 1 we can say that HFS is unaffected by the unbalanced voltage but it is affected by the magnetic saturation of motor, when load fluctuates, when voltage deviates, noise occurs etc. Similarly, GRT also remained unaltered with deviations in voltage and magnetic saturation. But the effect of voltage unbalance and load level on the index is not known yet.

Similarly from Table 2 we can say that neither it is easy to measure HFS nor it diagnose the intensity of fault precisely. But developed GRT can easily be measured and calculated and both the type and intensity of fault are diagnosed precisely.

5. Conclusion

In this paper first, we have discussed the eccentricity and its different types. Then we discussed the causes, effects and consequences of eccentricity. Then in Section 3 of this paper different indices are mentioned along with nature and behavior they show towards different changes. At last a brief tabular comparison is made between all the indices corresponding to different variations and their relative advantages. It can be said that the gyration radius of the torque developed (GRT) is the best index for detection and diagnosis of eccentricity fault. The researchers can use the results of this paper to choose the appropriate fault index in order to get better results. Moreover, it is beneficial for the manufacturers too. Considering the strength and weakness of indices they can apply the amendments at the manufacturing stage.

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