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New Vision about the Overlap Frequencies in the MCSA-FFT Technique to Diagnose the Eccentricity Fault in the Induction Motors

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Abstract— **This paper presents a new precise vision to diagnose the eccentricity fault using the motor current signature analysis technique (MCSA). The MCSA method was based on analyzing the FFT of the stator current. But, it has many disadvantages, as operating regimes (non-stationary) or his suffering to distingue the characteristic frequencies of several faults such as short circuit, eccentricity, broken rotor bars, etc. Our study will clarify the essential points of overlap in this method under static and dynamic eccentricity fault (SE and DE). This study proposes a development of the new formulas which precisely shows the overlap between the frequencies. According to MCSA method, we treated their problems in detail for eccentricity fault in the induction motors, while being based on the stator current spectrum. In this paper, experimental results were exploited under static and dynamic eccentricity fault.**

Keywords-dynamic eccentricity, induction motors, motor current signature analysis (MCSA), spectral analyses (FFT), static eccentricity

I. INTRODUCTION

Electrical machines required monitoring and diagnostic techniques. We have several diagnostic techniques, but each one has its advantages and disadvantages. In preventive maintenance, early detection is a very important factor to implement any method. The faults have several symptoms; these can be different or similar to other faults. We notice for example bearing faults, eccentricity, broken rotor bars, short circuit and other faults. Several studies have been carried out to these faults using the MCSA method [1-3]. The air-gap is not uniform under static or dynamic eccentricity, bearing fault [4-7].

Many studies treated the different faults such as: eccentricity, bearing faults in the induction machine by several techniques [8-11]. [12-14] have been used analytical models for dedicated to the fault detection in induction motor. Usually, simplicity and accuracy of the method to be used in diagnosis are important factors. Many works analyze this mechanical fault by the vibration analysis method [15-17]. MCSA has some advantages such as the simplicity of the current measuring. In this method, either the appearance of new frequency components around the fundamental or principal slot harmonics (*PSHs*) or the variation of their amplitude values, are frequently used to diagnose some faults in induction motors [1-3].

In this paper, we have chosen an interesting method which is MCSA-FFT. Our study based on the verification of characteristic frequencies for two types of eccentricity (SE and DE) in the stator current spectrum.

We have demonstrated analytically the formulae which show the overlap or ambiguity between frequencies. Many researchers confirm the difficulty to diagnose the fault of the eccentricity fault [18-19]. Moreover, Nandi et al. proposes some conditions in advance in order to have a judicious decision about the existence or the absence of the static or dynamic eccentricity fault [20]. Our work will confirm precisely this difficulty by well-defined formulas.

The experimental results were analyzed by the MCSA for induction machines with static and dynamic eccentricity.

II. REALIZATIION OF ECCENTRICITY FAULT

The experimental studies were conducted using a machine of 3 phases, 50 Hz, 28 rotor bars, 3kw (4.08HP) and 2 pole pairs. The motor current stator was used for two types of eccentricity.

In general, there are two types of air-gap eccentricity, the static and the dynamic eccentricity (SE, DE). The existence of both eccentricities called the mixed-eccentricity (ME). In the ideal case the stator and rotor have the same geometric axis, in the case of static eccentricity the rotor rotates around its own geometric axis, which is not the geometric axis of the stator, in case of dynamic eccentricity; the rotor is not concentric and

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rotates around the geometric axis of the stator. In reality, both eccentricities (static and dynamic) exist.

The induction motor has two bearings; static and dynamic eccentricity were introduced by using eccentric cut rings between the end bracket-bearing and the shaft- bearing respectively (Fig. 1).

Eccentricity means a non-uniform air gap between the stator and rotor. In practice, the air - gap eccentricity may be caused by many different factors; unbalanced load, bearing wear, bent rotor shaft and mechanical resonance at critical load. It is the reason that leads to unbalanced magnetic forces that act both on the rotor and stator of the motor, with excessive vibration and acoustic noise.

Fig. 1. Creation of static and dynamic eccentricity of δ_s=45% and δ_d=30% (degree of eccentricity) by an additional ring.

It is well known that a stator current signal contains important information about the electrical and/or mechanical faults of an induction motors. The literature reports that each fault is characterized by a characteristic harmonic in the stator current spectrum. An eccentricity fault (SE or DE) produces in the spectrum generally these frequencies:

$$f_{se-de} = \left[\left(k\lambda_{rb} \pm n_d\right)\frac{(1-s)}{p} \pm \nu \right].f_s \qquad (1)$$

where n_d =0 in case of static eccentricity, n_d = 1, 2, 3 ... in case of dynamic eccentricity (n_d is known as eccentricity order), f_s is the fundamental supply frequency, λ_{rb} is the number of rotor bars, s is the slip, p is the number of pole pairs, k is any integer, and ν is the order of the stator time harmonics that are present in the power supply driving the motor (ν = 1, 3, 5, ...).

In the case of mixed eccentricity can be expressed as follows:

$$f_{Mix-Ecc} = \left|f_s \pm kf_r\right| \qquad (2)$$

where f_r , is the mechanical rotor frequency.

III. Eccentricity Fault Signature

Our work is to detect the signature of eccentricity fault in the induction motor. The stator current analysis has been examined at stationary state. The information contained in the stator currents allows a judicious decision for the detection of the eccentricity fault. Normally, the eccentricity causes additional harmonics in the spectrum of the electric current. These harmonics depend on the number of pole pairs and the number of rotor bars.

It is necessary to indicate the conditions of existence or absence of the eccentricity defect proposed by Nandi et al. Nandi et al. studied the conditions of appearance of the rotor slot harmonics in the spectrum of the stator current, according to the following formula [20, 21]:

$$\lambda_{rb} = 2.p.\left[3.(m \pm n) \pm r\right] \qquad (3)$$

with, $m \pm n$ =0, 1, 2, 3...; r =0 ou 1.

It is clear that the combination of the number of pole pairs and the number of bars determines the existence of *RSHs*.

If λ_{rb} / p is not an integer, the existence of *PSHs* is not possible. Indeed, this proposition is verified for our machine. For a number of pairs of poles equal to 2 and a 28 rotor bars, we find:

$$\lambda_{rb} = 2.p.\left[3.(m \pm n) \pm r\right] = 28 = 2.(2).\left[3.(2)+1\right] = 28$$

The second condition is the existence of the characteristic frequencies of the faults. [21] Proposed the formula below which ensures the appearance of harmonics concerning a purely static or purely dynamic defect:

$$\lambda_{rb} = 2.p.\left[3.(m \pm n) \pm r\right] \pm d \qquad (4)$$

with, $m \pm n$ =0, 1, 2, 3,..., r =0 ou 1 ; d=1 ou 2. It is important to point out the importance of formulas (3), (4) in order to detect the eccentricity fault.

IV. Analysis of Eccnetricty Fault

A. Static Eccentricity

In this first part, we will present the experimental tests for different load (at no-load and at full load). The stator current spectrum allowed us to verify the characteristic frequencies according to SE fault.

Fig. 3 and Fig. 4 show the stator current spectrums around the fundamental for the healthy and faulty induction motor under static eccentricity.

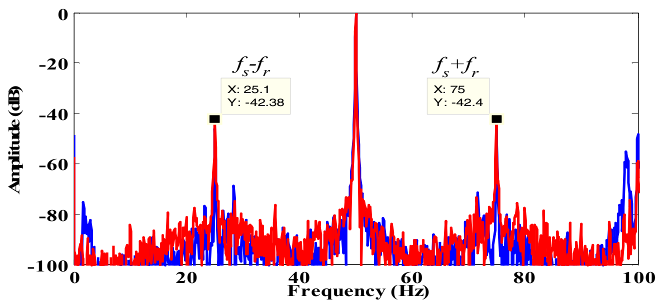

Fig. 3. Current spectrum of healthy (blue) and faulty (red) motor at no load (s=0.004,δ_s=45%,100Hz).

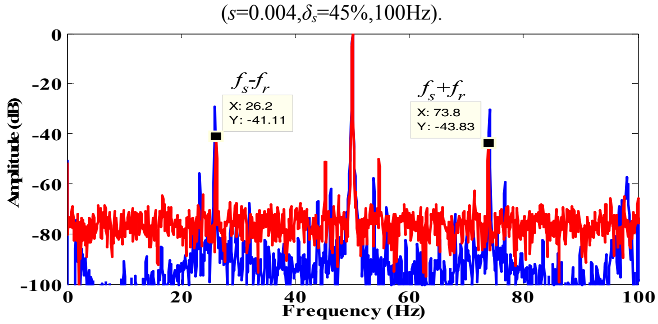

Fig. 4. Current spectrum of healthy (blue) and faulty (red) motor at full load, (s=0.048, δ_s=45%, 0-100Hz).

We can clearly notice characteristic frequencies components of mixed eccentricity at given by the equation (2). We present this example to at no-load machine operation and for k=1, we find f_s+f_r = 74.9 Hz and f_s-f_r = 25.1 Hz.

Practically, we have strengthened the static eccentricity compared to the dynamic eccentricity. This indicates that the mixed eccentricity is always present in our experimental test.

Fig. 5 and Fig. 6 illustrate the frequency content of the stator current spectrum at different frequency band and for motor operation at no-load.

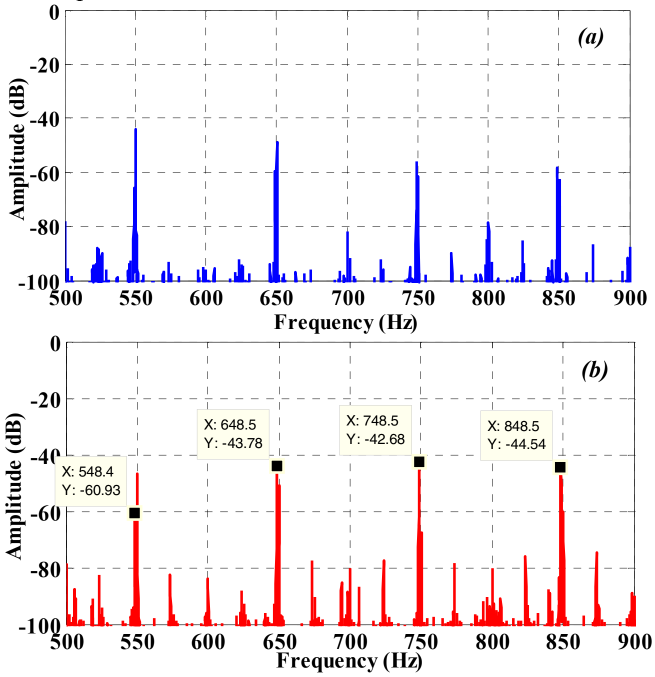

Fig. 5. Current spectrum of healthy (a) and faulty (b) motor at no load (s=0.004, δ_s=45%, 500-900Hz).

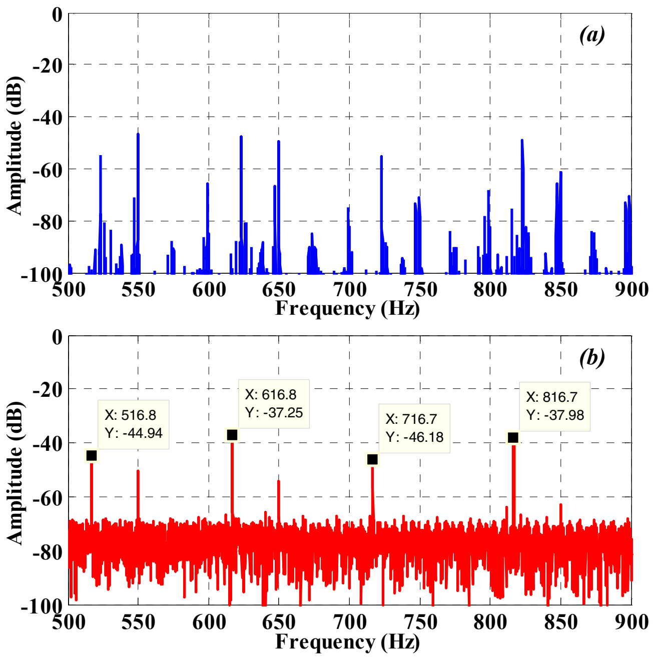

Fig. 6. Current spectrum of healthy (a) and faulty (b) motor at full load, (s=0.048, δ_s=45%, 500-900Hz).

The spectra presented above shows clearly which no additional frequency can arise due to static eccentricity!?

The question that arises at this time,

The question that arises is this: how to verify the formula (1)?

However, there has been a change in the amplitudes for the rotor slot harmonics.

The calculation of the frequencies characteristic of the static eccentricity fault is based on formula (1). We have found the frequencies for different values of k and v.

***k*=1, *v*=1 and *s*=0.004 (at no-load):**

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)+v\right].f_s=f_{se}(+)=747.2Hz$$

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)-v\right].f_s=f_{se}(-)=647.2Hz$$

***k*=1, *v*=3 and *s*=0.004 (at no-load):**

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)+v\right].f_s=f_{se}(+)=847.2Hz$$

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)-v\right].f_s=f_{se}(-)=547.2Hz$$

We verified the characteristic frequencies in the case of an induction machine operating at full load are:

***k*=1, *v*=1 and *s*=0.048 (at full load):**

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)+v\right].f_s=f_{se}(+)=716.4Hz$$

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)-v\right].f_s=f_{se}(-)=616.4Hz$$

***k*=1, *v*=3 and *s*=0.048 (at full load):**

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)-v\right].f_s=f_{se}(-)=516.4Hz$$

$$f_{se}=\left[\frac{k\lambda_{rb}}{p}(1-s)+v\right].f_s=f_{se}(+)=816.4Hz$$

B. *Dynamic Eccentricity*

The second section of this study consists in using an expression which depends on the equation (1) with the DE. The fault information must be extracted from the spectrum for two states: healthy and faulty induction motors.

Equation (1) gives rise to frequencies for harmonics relating to the eccentricity fault. We have found the frequencies due to mixed eccentricity in the stator current spectrum at no-load or full load, which can be derived from equation (2).

In reality, we have strengthened the dynamic eccentricity compared to the static eccentricity. This indicates that the mixed eccentricity is always present.

Fig. 7 and Fig. 8 clearly show additional frequencies caused by dynamic eccentricity for both conditions: no-load and full load.

We can say that these results are indicators of the dynamic eccentricity fault. We even see an increase in amplitude of the harmonics of the fault and the decrease of other as 650 Hz.

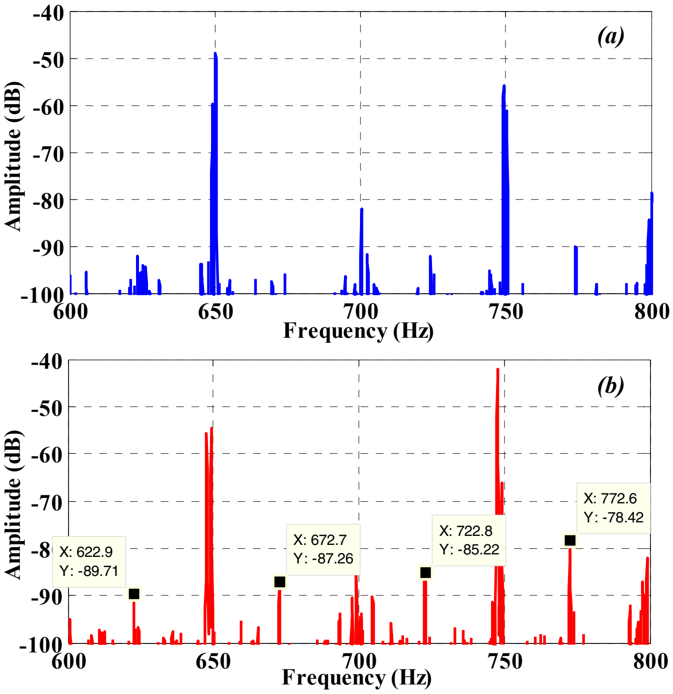

Fig. 7. Current spectrum of healthy (*a*) and faulty (*b*) motor at no load, (s=0.004, n_d=1).

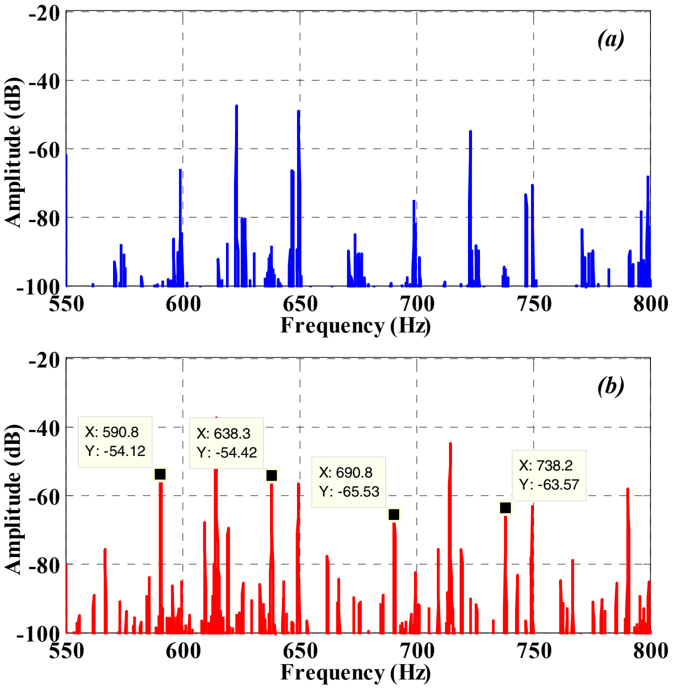

Fig. 8. Current spectrum of healthy (*a*) and faulty (*b*) motor at full load (s=0.052, n_d=1).

By installing of the two figures which show the additional frequencies caused by this fault. Fig. 9 illustrates the stator current spectrum for both cases.

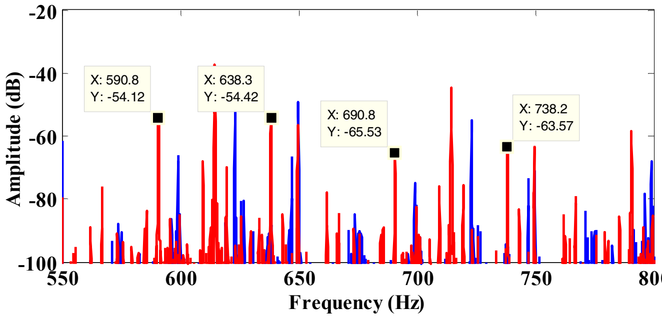

Fig. 9. Current spectrum of healthy (blue) and faulty (red) motor at full load (s=0.052, n_d=1).

The characteristic frequencies are verified according to formula (1) as follows:

s=0.004, k=1, n_d=1 and ν=1 (at no-load):

$$f_{de} = \left[(k\lambda_{rb} + n_d)\frac{(1-s)}{p} + \nu \right].f_s = f_{de}(++) = 772.1Hz$$

$$f_{de} = \left[(k\lambda_{rb} + n_d)\frac{(1-s)}{p} - \nu \right].f_s = f_{de}(+-) = 672.1Hz$$

$$f_{de} = \left[(k\lambda_{rb} - n_d)\frac{(1-s)}{p} - \nu \right].f_s = f_{de}(--) = 622.3Hz$$

s=0.052, k=1, n_d=1 and ν=1 (at full load):

$$f_{de} = \left[(k\lambda_{rb} + n_d)\frac{(1-s)}{p} + \nu \right].f_s = f_{de}(++) = 737.3Hz$$

$$f_{de} = \left[(k\lambda_{rb} - n_d)\frac{(1-s)}{p} + \nu \right].f_s = f_{de}(-+) = 689.9Hz$$

$$f_{de} = \left[(k\lambda_{rb} + n_d)\frac{(1-s)}{p} - \nu \right].f_s = f_{de}(+-) = 637.3Hz$$

$$f_{de} = \left[(k\lambda_{rb} - n_d)\frac{(1-s)}{p} - \nu \right].f_s = f_{de}(--) = 589.9Hz$$

V. Analysis and Discussion

A. *Static Eccentricity*

We observed in this work a good correspondence between the experimental results and the theoretical formulae. However, we have another formula for the *rotor slot harmonics* (f_{RSHs}). It ensures *equality* with the formula of characteristic frequencies in case of *static eccentricity*.

$$f_{RSHs} = f_{stat-ecc} = \left[\frac{k\lambda_{rb}(1-s)}{p} \pm \nu \right].f_s \qquad (5)$$

This similarity with static eccentricity fault leads us to speak of an *ambiguity* between the two phenomena.

Therefore, if the induction motor has both *PSHs*, this causes the creation of other higher order frequency components around 3, 5, 7, etc. These frequencies generally have not insignificant amplitudes.

B. Dynamic Eccentricity

The same problem was found in dynamic eccentricity fault. We have verified the ambiguity with other frequencies such as mixed eccentricity. The DE fault was checked with other conditions and combinations. It is also permissible that pure DE fault cannot exist alone, and that it always exists with a certain degree of residual static eccentricity which leads us to the third type of eccentricity (it is the ME).

Purely dynamic eccentricity fault components are produced near the rotor slots harmonic frequencies as shown in Fig. 7. These characteristic frequencies are due the dynamic eccentricity, and we can found it by replacing n_d=1 in equation (1).

First of all, it is essential to specify the *overlap* with the mixed eccentricity at no-load. For purely dynamic eccentricity fault, there is a correspondence between formula (2) and relation (1). In this case, there is an *ambiguity* between the two phenomena.

For dynamic eccentricity, we write:

$$f_{dyn-ecc}=\left[\;k\lambda_{rb}\frac{(1-s)}{p}\pm\nu\pm n_d\frac{(1-s)}{p}\;\right].f_s$$

In the case where the motor operates at full load ($s\neq 0$):

$$f_{dyn-ecc}=\left|(k\lambda_{rb}\pm n_d)\frac{(1-s)}{p}f_s\pm\nu f_s\right| \qquad (6)$$

$$f_{dyn-ecc}=\left|\nu f_s\pm k'\frac{(1-s)}{p}f_s\right|=\left|\nu f_s\pm k' f_r\right|$$

with: $k'=(k\lambda_{rb}\pm n_d)$ is an integer.

To clarify the *overlap* and the degree of similarity with the *mixed eccentricity* fault, we replace *v* by 1:

$$f_{dyn-ecc}=\left|f_s\pm k' f_r\right|=f_{Mix-ecc} \qquad (7)$$

It is concluded that there is a difficulty in detecting a dynamic eccentricity fault in the presence of another degree of static eccentricity. Then the two eccentricities produce a mixed eccentricity.

The second problem lies in another series of harmonics which connect all the characteristic frequencies of *dynamic eccentricity fault* and the *rotor slots harmonic*.

In the first case, the machine operates at no-load:

$$f_{dyn-ecc}=\left[\;\frac{k\lambda_{rb}}{p}\pm\nu\pm\frac{n_d}{p}\;\right].f_s$$

$$f_{dyn-ecc}=f_{RSHs}=\left[\;\frac{k\lambda_{rb}}{p}+n_{dRSH}\;\right].f_s \qquad (8)$$

with,

$$n_{dRSH}=\pm\nu\pm\frac{n_d}{p} \qquad (9)$$

The induction machine has 2 pole pairs, the overlap exists between f_{RSHs} and $f_{dyn-ecc}$ if and only if:

$$n_{dRSH}=\pm\nu\pm\frac{n_d}{p}=3,5,7,...$$

The condition which satisfies this equality is the following:

$$n_d=4(n+1) \qquad (10)$$

Such as:

$$n=0,\,1,\,2,\,3,\,4,\,5,\,...$$

VI. Conclusion

In this paper, the application of the motor current signature analysis (MCSA) technique to diagnose the air gap-eccentricity fault in three-phase induction motors has been presented. The detection of eccentricity fault in stator current spectrum around the *PSHs* is effective only for some combination of number of pole pairs and rotor slots.

The overlap between the fault characteristic frequencies and other frequencies (*RSHs*) was observed.

We have specified the overlapping formulae for both types of eccentricities (static and dynamic). Our analysis demonstrated good resolve about this ambiguity for SE and/or DE. Fault information is overlapping when, comparing the spectra of two machine states.

Experimental results for the healthy and faulty state are presented; all depends on the motor design. The results show the suffering of MCSA method to detect the eccentricity faults.

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