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Detection of Mechanical Imbalances of Induction Motors with Instantaneous Power Signature Analysis

Ahmet Kucuker† **and Mehmet Bayrak***

Abstract – Mechanical imbalances are common mechanical faults in induction motors. Vibration monitoring techniques have been widely used for the diagnosis of mechanical faults in induction motors, but electrical detection methods have been preferred in recent years. For many years, researchers have concentrated on the Motor Current Signature Analysis (MCSA). This paper examines the effect of mechanical imbalances to induction machine electrical parameters. Instantaneous Power Signature Analysis (IPSA) technique used to detect these faults. In the paper, a full analysis of the proposed technique is presented, and experimental results for healthy and faulty motors have been shown and discussed.

Keywords: Instantaneous power signature analysis, Mechanical imbalance, Motor faults

1. Introduction

Induction motors play an important role to ensure the sustainability in the processes and production lines in many areas of industry. Motor failures, can cause unexpected problems or shut down of the production processes. Detection of these faults which affects the reliability of the processes has come into prominence. Therefore; preventive maintenance, diagnostics, protection of induction motor becomes increasingly important nowadays.

Motor faults can be classified as mechanical faults and electrical faults. This paper examines the effect of mechanical imbalances to the induction machine electrical parameters. Mechanical imbalances such as rotor unbalance, shaft misalignments and mechanical load imbalances reserve significant portion of the faults related with induction motor as seen in Table 1 [1-3]

Table 1. Percentage of failure by component

Fault Types	IEEE	EPRI
Bearing Faults	%44	%41
Stator Faults	%26	%36
Rotor Faults	%8	%9
Other Faults	%22	%14

Static eccentricity, dynamic eccentricity and mechanical load imbalance terms are the types of rotor imbalances. Eccentricity problems are related to the other electric motor problems, such as mechanical unbalance, bearing and misalignment problems. There is an air gap between rotor and stator in induction motors and eccentricity problem is about these air gap changes. Static eccentricity can be caused by faulty rotor position or stator core ovality. The force called as unbalanced magnetic pull, which tries to increase the eccentricity level, occurs because of rotor axis displacement from the stator axis and the angular velocity of the eccentric rotor motion. Furthermore, it may cause serious damage to the electrical machine. However, dynamic eccentricity is related to static eccentricity [4, 5]. Dynamic eccentricity occurs when the rotor is not in the center of rotation. Dynamic eccentricity can be caused by mechanical resonance, bearing wear or bearing problems [6, 7].

Several problems occur from eccentricity, including; risk of the rotor contact to the stator, make additional stresses on the motor bearings, reducing bearing life, produce magnetic pulse waves that make electrical and mechanical stress on the winding.

Therefore; it is very important to detect mechanical faults. Many studies have been done to detect these faults. Several of these studies proposed techniques for the detection of mechanical faults through the use of the vibration signals which has some disadvantages such as high cost of development and maintenance [8-11]. Current monitoring techniques like MCSA (Motor Current Signature Analysis) take the place of vibration monitoring techniques, which have been used many years [12-17].

Due to the small amplitude of the fault harmonics in current spectrum, MCSA may lead to wrong diagnosis. Motor power signature analysis considered as a more convenient and reliable method for the detection of the fault [21]. In this paper, proposed technique instantaneous power signature analysis has been developed by using three-phase currents and voltages. Consequently, motor current and voltage harmonics reflect to the instantaneous power signature.

Ideal centric conditions cannot be provided. Any real machine has an inherent level of eccentricity. The effects of

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mixed eccentricity condition and mechanical imbalances cause characteristic sideband currents in the current spectrum. These frequencies are given by (1), where f_s is supply frequency, f_r is rotational frequency, k is the (integer) order number, s is the slip, and p is the number of poles [12, 13, 18].

$$f_{ecc,i} = f_s\left(1 \pm k\frac{1-s}{p/2}\right) \tag{1}$$

Torque oscillations due to unbalanced pulley, load or clutch causes mechanical imbalance and these oscillations are related to the induction motor speed. They give rise to current harmonics as presented by Eq. (1). The interaction of those harmonic components with the mainly supply voltage induces imbalance harmonics in the power spectrum as seen in Eq. (3).

$$f_r = \frac{1-s}{p/2}.f_s \tag{2}$$

$$f_{ecc,p} = f_s k\frac{1-s}{p/2} \tag{3}$$

This paper proposes the instantaneous power analysis usage for detection of mixed eccentricity or mechanical imbalance. It is shown by imbalance indicator, which indicates the percent increase in the specific imbalance harmonics FFT magnitude level.

2. The Proposed Detection Technique

Suppose that, an induction motor energized by an ideal three-phase voltage and v_{LL} is the voltage between any two phases, i_L is the current of these phases. Instantaneous power can be defined by the Eq. (4).

$$p(t) = \sqrt{3}v_{LL}i_L \tag{4}$$

2.1 Instantaneous power of healthy induction motor

The line voltage v_{LL}, stator current i_L, partial instantaneous power $p_0(t)$ can be written with equations (5), (6) and (7), where U_m is the maximum value of the line to line voltage, I_m is the maximum value of the supply current, θ is the motor load angle, f is the supply frequency, by neglecting inherent asymmetry of normal induction motor.

$$v_{LL}(t) = U_m\cos(2\pi ft) \tag{5}$$

$$i_L(t) = I_m\cos(2\pi ft - \theta) \tag{6}$$

$$p_0(t) = \frac{U_m I_m}{2}\cos\left[2\pi(2f)t - \theta\right] + \frac{U_m I_m}{2}\cos(\theta) \tag{7}$$

The total instantaneous power of a healthy induction motor can be calculated by the Eq. (8) using the three phase measured instantaneous voltages and currents.

$$p_{tot} = v_1(t)i_1(t) + v_2(t)i_2(t) + v_3(t)i_3(t) \tag{8}$$

2.2 Instantaneous power of faulty induction motor

If a mechanical imbalance takes place in induction motor, fault characteristic components at f_{ecc} appear in the stator current, α_1 is the initial phase angle at a frequency $f_{ecc,1}$ and α_2 is the initial phase angle at a frequency $f_{ecc,2}$ [19, 20, 22].

$$f_{ecc,1} = f_s + kf_r \tag{9}$$

$$f_{ecc,2} = f_s - kf_r \tag{10}$$

$$i_{L,ecc}(t) = \left\{\begin{matrix} I_m\cos\left[2\pi ft - \theta\right] + \\ \sum\limits_{k=1}^{\infty}\left\{\begin{matrix} I_{ecc,k_1}\cos\left[2\pi f_{ecc_1}t - \alpha_1\right] + \\ I_{ecc,k_2}\cos\left[2\pi f_{ecc_2}t - \alpha_2\right] \end{matrix}\right\} \end{matrix}\right\} \tag{11}$$

The equation for the partial instantaneous power in the case of an eccentricity fault is given by (12) [19, 20, 22]. It can be seen that the instantaneous power spectrum contains an additional component at the modulation frequency.

$$p_{ecc}(t) = p_0(t) + \sum_{k=1}^{\infty}\left\{\begin{matrix} \frac{U_m I_{ecc,k_1}}{2}\cos\left[2\pi(2f_s - kf_r)t - \alpha_1\right] \\ + \frac{U_m I_{ecc,k_1}}{2}\cos\left[2\pi(kf_r)t + \theta_1\right] + \\ \frac{U_m I_{ecc,k_2}}{2}\cos\left[2\pi(2f_s + kf_r)t - \alpha_2\right] \\ + \frac{U_m I_{ecc,k_2}}{2}\cos\left[2\pi(kf_r)t + \theta_2\right] \end{matrix}\right\} \tag{12}$$

The total instantaneous power spectrum contains only a dc level and an additional component at f_r frequency [22]. The total instantaneous power is given by Eq. (13).

$$p_{tot,ecc}(t) = \left\{\begin{matrix} p_{tot,0}(t) + \\ \sum\limits_{k=1}^{\infty}\left\{\begin{matrix} \frac{\sqrt{3}U_m I_{ecc,k_1}}{2}\cos(\theta)\cos\left[2\pi(kf_r)t + \theta_1\right] + \\ \frac{\sqrt{3}U_m I_{ecc,k_2}}{2}\cos(\theta)\cos\left[2\pi(kf_r)t - \theta_2\right] \end{matrix}\right\} \end{matrix}\right\} \tag{13}$$

2.3 Detection of imbalance

The signal characteristics (such as magnitude of a frequency component of a signal) for indicating existence or level of fault magnitude named as a fault indicator.

Ideal fault indicator should exhibit a measurable change when the imbalance level increases with the size of the fault. In addition, a fault indication should have small, or otherwise consistent, variation with load and should be independent of other faults.

In this study, fault indicator is the percent increase in the specific imbalance harmonics at instantaneous power spectrum. Under load conditions, a new imbalance fault indicator has been determined. This is the frequency bandwidth that centers the imbalance harmonic frequency. This imbalance indicator displayed in the user interface which prepared with Labview software. Thus, online motor imbalance fault detection software has been created.

3. Experimental Results

In the experimental studies, 4 pole 50 Hz 3kW induction motor has been used and mechanical imbalance system made with unbalanced pulley. Experiments are implemented due to the scheme given by Fig. 1.

For a four pole induction motor operated at 50 Hz, with no load $s \approx 0$, mechanical imbalance frequency reflected to instantaneous power is 25 Hz, which has computed from the Eq. (3).

For no load condition it is clearly seen as percent

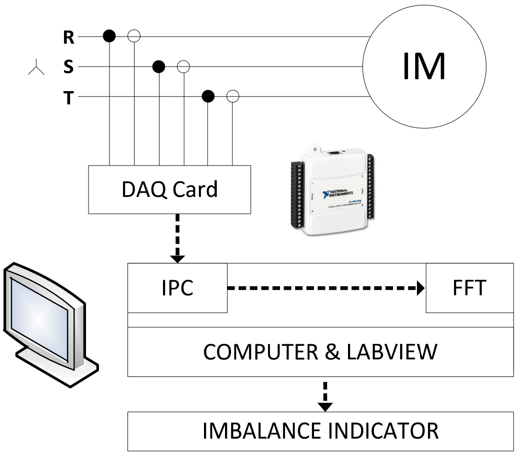
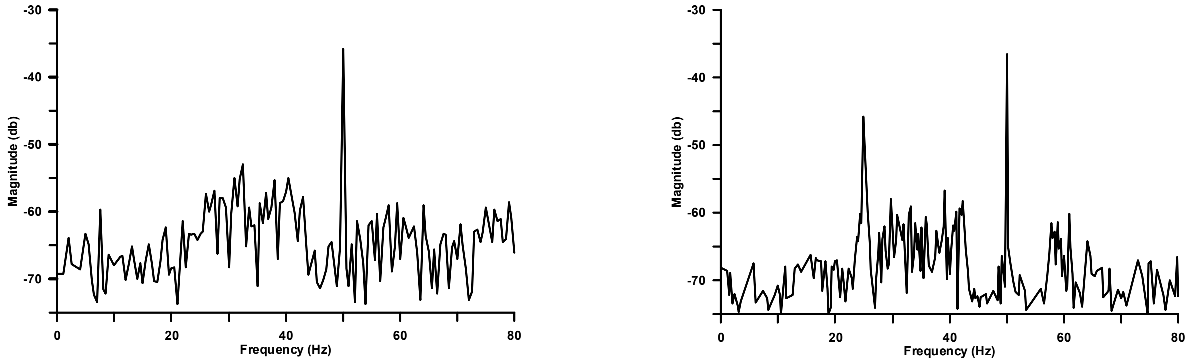


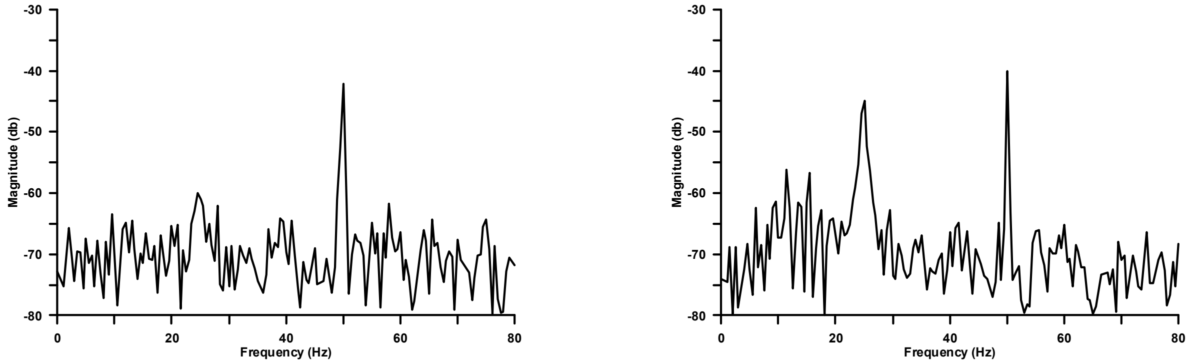
Fig. 1. Detection System Scheme. DAQ: Data Acquisition Card, IPC: Instantaneous Power Computing, FFT: Fast Fourier Transform



(a) Healthy Motor

(b) Mechanical Imbalanced Motor

Fig. 2. IPSA Under No Load



(a) Healthy Motor Under %25 Load

(b) Mechanical Imbalanced Motor Under %25 Load

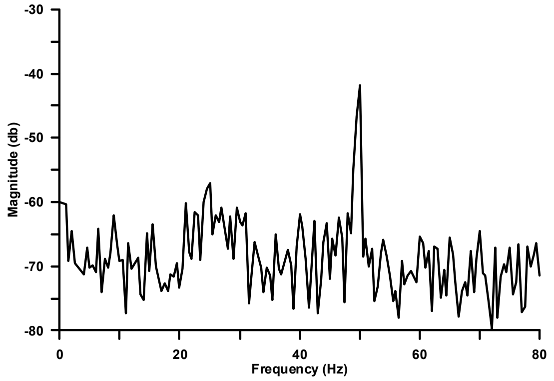
Fig. 3. IPSA Under %25 Load

Table 2. Experimental Results

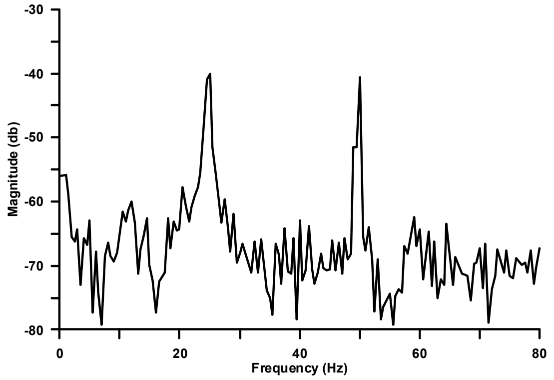
Condition	Percent increase in mechanical imbalance indicator value
No Load	31,27
%25 Load	25,52
%50 Load	24,25

Table 3. Frequency Bandwidth Indicator Values

Condition	Frequency Band Left Bound (Hz)	Frequency Band Right Bound (Hz)	Frequency Bandwidth (Hz)
No Load	25	25	0
%25 Load	22,5	27, 5	5
%50 Load	20,5	29,5	9



(a) Healthy Motor Under %50 Load



(b) Mechanical Imbalanced Motor Under %50 Load

Fig. 4. IPSA Under %50 Load

increase in mechanical imbalance indicator value.

The percent increase in mechanical imbalance indicator value is given for load condition by Table 2. It shows that values are decreasing due to load ratio increase. Even though the small decrease in the value of the imbalance indicator, it can be used for detection of imbalance problems. The difference between healthy and faulty situations with no load can be clearly seen from Figs. 2 (a) and Fig. 2 (b).

Fig. 3 shows the difference between healthy motor and mechanical imbalanced motor with %25 load condition. Also for %50 load condition Fig. 4 shows the difference. The imbalance frequency 25Hz component can be clearly seen from Figs.3 (b) and Fig. 4 (b).

Under load conditions the imbalance can be also seen in the difference of the frequency bands. This imbalance indicator is the frequency bandwidth that centers the imbalance harmonic frequency. Frequency bandwidth occurs because of slip in induction motor. Hence frequency bandwidth gets wider due to load increase. At the same time, magnitude levels of imbalance harmonic frequency increases in direct proportion to load level.

Table 3 gives the experimental results for the imbalance indicator under load conditions. Increasing of frequency bandwidth observed from the experimental results and Figs. 3(b), Fig. 4 (b).

4. Conclusion

The feasibility and effectiveness of the proposed system have been demonstrated with laboratory experiments on a three-phase induction motor.

As a conclusion, results have shown that mechanical load imbalances and eccentricity in an induction motor could be detected using simple and low-cost techniques that utilize the instantaneous power measurements. The presence of these mechanical faults was detected by the percent increase in the specific imbalance harmonics in the instantaneous power. Furthermore, an imbalance indicator determined under load conditions named as “imbalance frequency bandwidth” that centers the imbalance harmonic frequency. In other respects, the instantaneous power usage for the detection of mechanical imbalance condition provides information about the current and voltage values, which may be important when unbalanced voltage, voltage sags and abnormal other electrical faults occur.

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