Wireless Health Monitoring System for Rotor Eccentricity Faults Detection in Induction Machine

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Abstract. *Condition monitoring and fault detection of induction machines become an important area of research. Many techniques have been applied in this field including vibration, thermal, chemical and acoustic emission monitoring, but Motor Current Signature Analysis monitoring techniques usually are applied to detect the various classes of induction machine faults such as rotor, short winding, eccentricity and bearing fault etc. This paper presents a wireless system detection for rotor eccentricity faults in induction machine based on LabVIEW platform. Moreover, it is demonstrated that eccentricity fault generates a series of low frequency components in the form of sidebands around the fundamental frequency and its harmonic. In addition, the amplitudes of those components increase in proportion to the load and fault severity. The Power Spectral Density techniques and Short Time Frequency Transform spectrogram of current signals are used to detect the presence of those fault signatures.*

Keywords

Eccentricity, condition monitoring, induction machine, stator current signature, wireless system.

Nomenclature

Fs	Stator supply frequency.
fr	Rotational frequency.
N_r	Number of rotor bars.
s	Slip.
p	Pole pair number.
MCSA	Motor Current Signature Analysis.
PSD	Power spectral density.
STFT	Short time Fourier transforms.
n_d	Eccentricity order.
h	Stator time harmonic (1, 3, 5, ...).
k	Any integer (0, 1, 2, ...).

1. Introduction

Condition Monitoring (CM) is an effective strategy to maintain the performance of modern industrial equipment. In developed countries, much of the energy in industry is consumed by motor systems. Among these, three-phase induction motors are dominant because of their robustness and easy maintenance [1] and [2]. Moreover Induction Machines (IM) are the most commonly type of electrical rotating drives used in industry. However, due to the combination of poor working environment and installation, internal faults frequently occur on rotor, such as broken rotor bars, end ring connectors, and rotor eccentricity [3], [4] and [5]. Most of the faults in IM have a relationship with air-gap eccentricity which is the condition of the unequal air-gap between the stator and the rotor. This fault can result from variety of sources such in a stator rotor rub, thereby causing severe damage to the motor as well as acoustic noise and vibration. The creation of an unequal air gap may involve many different factors including unbalanced load, bearing wear, bent rotor shaft, and mechanical resonance at the critical load [6] and [7].

For the purpose of detecting such fault-related signals, many diagnostic methods have been developed so far, such as electromagnetic field monitoring, temperature measurements, Radio-Frequency (RF) emissions monitoring, vibration monitoring, chemical analysis, acoustic noise measurements and Motor-Current Signature Analysis (MCSA). Both, Vibration [8] and

[9] and MCSA [4], [10] and [11] are well proven methods for electrical machines fault diagnostics, but can be classified as the most promising fault-detection method for IM faults and can be done either online or offline. A great number of researchers have reported success in using MCSA as fault detection method which is based on current monitoring of induction motor; therefore it is not very expensive. The MCSA uses the current spectrum of the machine for locating characteristic fault frequencies. To diagnose the rotor eccentricity fault, MCSA based fault detection techniques such as Fast Fourier Transform (FFT), Power Spectral Density (PSD), Short Time Fourier Transform (STFT) and Wavelet Transform (WT) are used to diagnose the faults of IM. In this paper, the PSD and STFT spectrogram of current signals are used to detect the presence of frequency fault of rotor eccentricity around the fundamental and its harmonics [12] and [13].

Eccentricity fault in induction machine is usually detected by analyzing the stator line current spectrum. To detect and diagnose the static eccentricity, dynamic eccentricity and mixed eccentricity using frequency spectrum of stator current, two fundamental parameters need to be calculated:

- frequency of sideband components due to eccentricity fault around fundamental and
- frequency of sideband components due to eccentricity fault around the 3rd harmonic [14].

It is notable that low frequency components are more sensitive to torque variations. In addition, eccentricity fault and variation of the load does also affect considerably the above mentioned parameters. In this case, eccentricity fault detection is more challenging, because more sophisticated signal processing is required. For this purpose, time-frequency domain signal processing instantaneous frequency of fault components has been employed to detect and diagnose of mixed eccentricity fault [15].

The paper is organized as follows: Section 2. describes the Theoretical background of origins and effects of eccentricity fault. Section 3. describes the Condition Monitoring Techniques. Section 4. presents the detailed hardware design for the Laboratory Experimental Setup. Section 5. deals with the measurement results. Finally, conclusions are given in Sec. 6.

2. Theoretical Background

Most of the faults in IM have a relationship with air-gap eccentricity which is a condition in which there is an uneven air gap between the stator and the rotor. Normally, the rotor that is centered at the stator bore of healthy motor results in identical air-gap among the stator and rotor. However, when the eccentricity emerges, it may lead to severe damage to the stator and rotor core. Thus, it is critical to detect the air gap eccentricity at an early stage to protect the motor system. In general, there are three forms of air-gap eccentricity: static, dynamic, and mixed. Static eccentricity (where the rotor is displaced from the stator bore center but is still turning upon its own axis), or dynamic eccentricity (where the rotor is still turning upon the stator bore center but not on its own center), if both static and dynamic eccentricities exist together then mixed eccentricity must be considered. In case of mixed eccentricity, the center of rotor, the center of stator, and the center of rotation are displaced with respect to each other. Figure 1 shows the cross sections of the induction motor with different types of eccentricities [14] and [16].

With MCSA, eccentricity can be detected by observing the rotor rotational speed frequency f_r and/or the rotor slot passing frequency components. The frequency equation for determining air-gap characteristics [13], [17] and [18] is as follows:

$$f_{ecc} = Fs\left[(k \cdot N_r \pm n_d)\frac{(1-s)}{p} \pm h\right], \tag{1}$$

where $n_d = 0$ in case of static eccentricity, and $n_d = 1, 2, 3, \ldots$; in case of dynamic eccentricity. Furthermore, if mixed eccentricity exist, the case in most air-gap related failures, there will be low-frequency components near the fundamental frequency and its harmonics which can be expressed by the following equation:

$$f_{Lecc} = h \cdot Fs \pm k \cdot fr. \tag{2}$$

However, in the line current spectrum of the faulty motor, the most important components are obtained around the fundamental frequency by substituting $k = 1$ as follows:

$$f_{Lecc} = Fs \pm fr. \tag{3}$$

Vibration signals can also be monitored to detect eccentricity faults. In case of mixed eccentricity, the low-frequency stator vibration components are given by [7] and [19]:

$$f_{Sv} = 2Fs \pm fr. \tag{4}$$

However, vibration sensors are delicate and expensive. They also have special installation requirements to avoid damage due to shock and vibration.

3. Condition Monitoring Techniques

Condition Monitoring (CM) techniques are effective to maintain the performance of modern industrial equip-

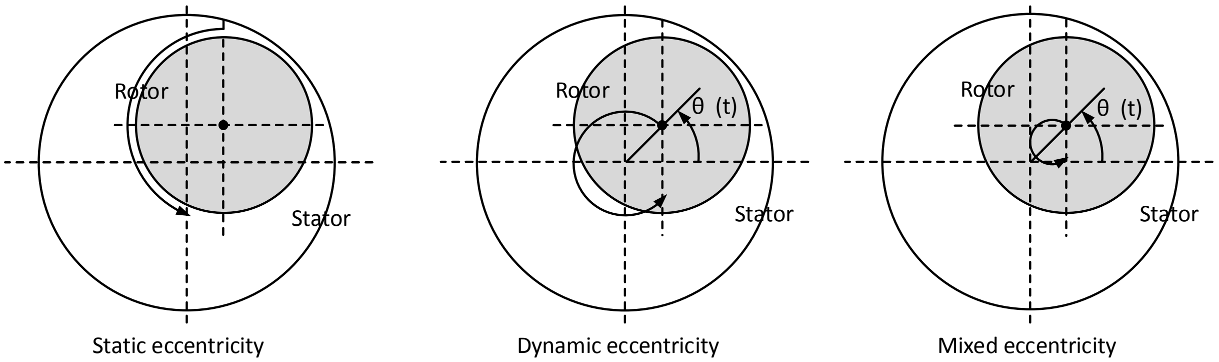


Fig. 1: Different types of eccentricity.

ment and have been successfully used by many industries to diagnose and identify the causes of machinery fault. Technically, IM CM methods are performed on-line or off-line. Off-line tests require the interruption of the motor operation or shutdown, while on-line methods provide motor diagnostics during the operation. However, on-line CM methods have attracted a great attention, as they offer adequate warning of the imminent failures, diagnosing present maintenance needs, schedule future preventive maintenance, and repair work [13].

Currently, Wireless System is gaining popularity in online CM fields and has been successfully employed in industry because of its inherent advantages, such as ease of installation, low cost, low latency, self-organization, and high reliability [2]. A block diagram

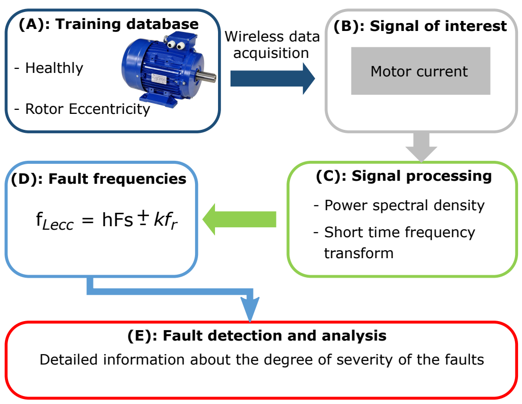


Fig. 2: Schematic diagram of the proposed fault detection procedure.

of a wireless CM system is shown in Fig. 2. In this stage, all the related terms used in CM during this study are described briefly. The experimental tests were developed under a variety of load conditions as mentioned in block (A). The eccentricity faults affect the symmetry of the machine and as a result produce characteristic fault frequencies. A wireless data acquisition system is used to acquire the motor current signals in digital form as shown in block (B). The signals can be analyzed by different digital signal processing techniques to extract features, which are sensitive to the presence of faults as mentioned in block (C). In next step, the characteristic fault frequencies of rotor eccentricity fault are detected from the processed signals as shown in block (D). Finally, in block (E), the fault frequency characteristics that relate to different fault conditions are analyzed. This helps to detect the eccentricity fault and tracks the evolution of fault components over time.

This paper presents the design of wireless CM system shown in Fig. 3. The wireless data acquisition system is used to record the current signals in digital form. These signals can be analyzed by different digital signal processing techniques (PSD and STFT) to extract features, which are sensitive to the presence of rotor eccentricity fault.

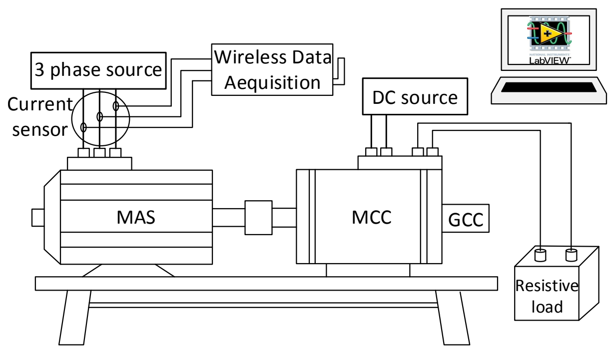


Fig. 3: Line diagram of the wireless monitoring system.

4. Laboratory Experimental Setup

The experimental system was conducted using the test rig and data acquisition system as shown in Fig. 4. The experimental tests were developed on a 3 kW, 50 Hz, 220 V = 380 V, 4-poles Induction Machine. The motor was directly coupled to a DC machine, which was loaded using a variable-resistance bank, the current of the motor is measured using LEM modules (LT 100-S/SP30) and converted to voltage signals. The voltage range was calibrated such that start-up currents measured by the sensor can fall within the voltage ranges on the input of the national instrument modules NI9222. These modules provide four differential analogue input channels with a ±10 V input range. All signals are sampled by wireless data acquisition device NI cDAQ-9191 and they are analyzed using the LabVIEW [18] and [20]. The cDAQ-9191 controls the timing, synchronization, and data transfer between C Series I/O modules and an external host. You can send data from the cDAQ-9191 to a host PC over Ethernet or IEEE 802.11 Wi-Fi.

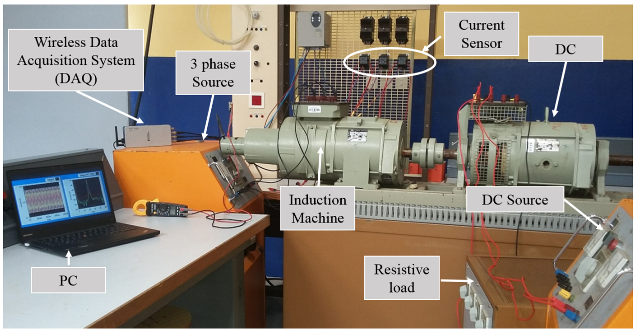


Fig. 4: Experimental setup.

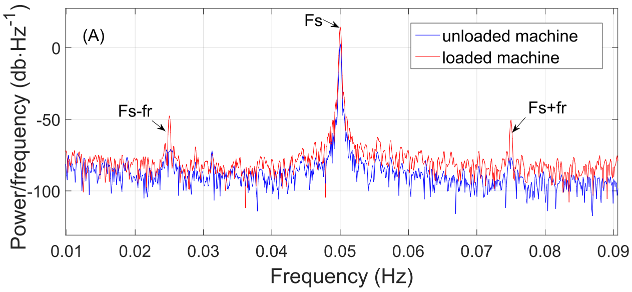
5. Measurement Results

The experiments test have been performed to detect mixed eccentricity faults under no load and loaded condition to study its effect on current components. The results obtained from these experiments are given below.

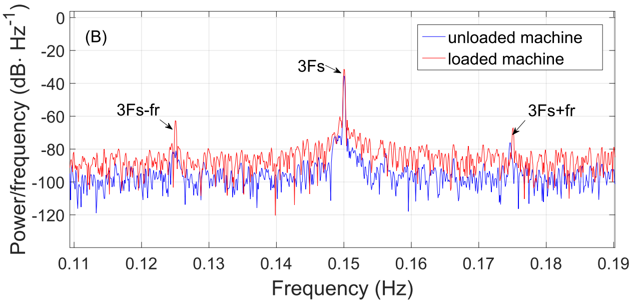
First, the IM was tested at no load condition so the results can be compared with the loaded test. Figure 5 shows the motor current power spectrum of faulty machine with Mixed Eccentricity under no load and loaded condition around fundamental and the 3rd harmonic. This power spectrum shows the fault frequencies at 25 Hz, 74 Hz, 125 Hz, and 174 Hz. It is observed from the figures that magnitude of those components increases in proportion to the load and severity of a fault. Table 1 shows the analysis of power spectrums of IM with mixed eccentricity.

Figure 6 shows the stator vibration spectrum of faulty machine with Mixed Eccentricity under loaded condition.

The Diagnosis in the time-frequency analysis can be performed through different continuous transforms such as STFT, CWT, WVD, etc. The standard result of these transforms is a two-dimensional graph usually plotted as a colored map. This map provides an information about the distribution of signal energy among different frequencies. This enables evolution tracking of fault components during transients and nonstationary operating conditions. Figure 7 shows the STFT spectrogram of faulty machine with Mixed Eccentricity under loaded condition around fundamental and the 3rd harmonic.



(a) Around fundamental.



(b) Around 3rd harmonic.

Fig. 5: Power spectrum of faulty machine with Mixed Eccentricity under no load and loaded condition.

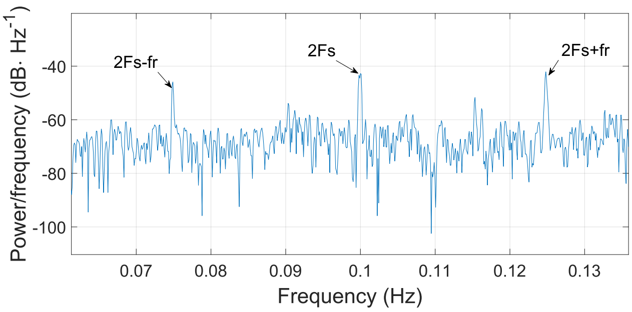


Fig. 6: Stator vibration spectrum of faulty machine with Mixed Eccentricity.

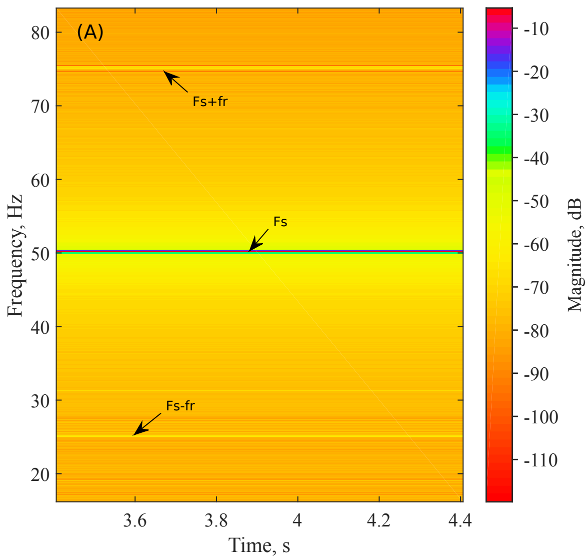
6. Conclusion

This paper presents a wireless system to perform real-time condition monitoring of induction machine for early detection and monitoring of rotor eccentricity fault. Moreover, in condition monitoring algorithms, measurements are taken for a loaded and unloaded induction machine at the time of commissioning by wireless data acquisition device. The fault algorithm moni-

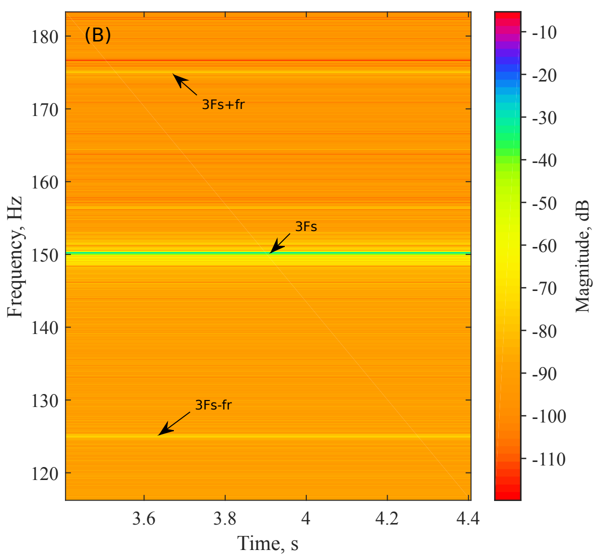
Tab. 1: Measurement results.

	Load Condition	Slip	Fault Frequency (Hz)				Magnitude Frequency (db)				Observations
			Fs-fr	*Fs+fr*	*3Fs-fr*	*3Fs+fr*	*Fs-fr*	*Fs+fr*	*3Fs-fr*	*3Fs+fr*	
Fig. 4	No load	0.0055	25.13	74.86	125.14	174.86	−76.66	−75.74	−92.06	−75.7	Magnitude increases with increase of load
	Loaded	0.0289	25.72	74.27	125.72	174.27	−47.77	−50.6	−62.96	−67.06	

tors the amplitude of fault frequencies and tracks the evolution of fault components over time. The wireless communications are based on the IEEE 802.11 Wi-Fi. This ensures the data transmission and a synchronous acquisition, which are critical elements in a condition monitoring system based on a wireless system network. Experimental results confirm the theatrical background of rotor eccentricity fault, and its usefulness for the preventive maintenance for induction machine.



(a) Around fundamental.



(b) Around 3rd harmonic.

Fig. 7: STFT spectrogram of faulty machine with Mixed Eccentricity under loaded condition.

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