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An on-line condition monitoring system for induction motors via instantaneous power analysis †

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Abstract

Condition monitoring is an important factor in assuring well-being of motors. Existing approaches of condition monitoring are dependent on expensive special sensors. This paper reviews various forms of existing condition monitoring methods and highlights the need for an economical intelligent fault diagnosis system. In this study, the methodology taken in developing a condition monitoring system for the motor bearing faults identification, utilizing the commonly available motor stator current and voltage is demonstrated. This unique diagnostic condition monitoring system provides continuous real time tracking of the various bearing defects and determines the severity which can be adopted for fast decision making. The study on different bearing faults under no-load and full-load conditions is carried out experimentally and analyzed, and the results on the real hardware implementation confirm the effectiveness of the proposed approach.

Keywords: Bearing faults; Condition monitoring; Fault diagnosis; Instantaneous power analysis

1. Introduction

The type of motors most often utilized in industries are the induction motors which make up 95% of the prime movers [1, 2]. These motors have been applied in various applications, such as the chemical processing plants, nuclear power plants, paper mills, cooling water systems and the mining industry. Although induction motors are very dependable with low failure rate and require only basic maintenance, still unprecedented breakdowns and failures may occur after some durations [2, 3] which can lead to production losses. Consequently, detecting initial failures and replacing damaged parts according to schedule will prevent the problems of unexpected breakdowns [2, 4]. The prevention of unscheduled downtime for electrical drive systems would help in reducing the costs associated with maintenance.

In recent years, the use of analysis methods together with the aid of systems of computerized data processing and acquisition has brought forth new areas in the research of condition monitoring for induction motors. As described in Refs. [5, 6] the computer and transducer technologies combine with the advanced signal processing methods have resulted in the ability to apply condition monitoring systems in a more effective manner, reliable with lower maintenance cost. The key point is, it remains necessary during the maintenance period that the data regarding the status of the machines be obtained by on-line condition monitoring and hence the machinery failure can be reduced more effectively.

Due to the broad applications of the on-line condition monitoring systems, the inclusion of a discussion, although not comprehensive, in this paragraph is important to help understanding the progress in this area. The on-line condition monitoring systems are being used in machines with built-in hydraulic drive systems, where constant monitoring of equipment status, as well as the hydraulic fluid is required. The on-line condition monitoring systems are used in petroleum industry to detect oil oxidation and changes in oil acidity. Similarly, on-line condition monitoring systems are being used to estimate the life of pumps, gears, shafts, CNC tools, wind turbines, hydro turbines, compressors, boilers and electric motors. In a recent paper, Ref. [7] presents a novel technique for the condition monitoring of hydraulic oils throughout their life-cycles. A hybrid mathematical model based on data from oil-ageing tests has been proposed in this paper. Earlier in a similar work, a short-overview of modern on-line condition monitoring techniques appropriate for monitoring hydraulic fluid and hydraulic drives is given in Ref. [8]. Interestingly in Ref. [9], a user friendly platform for wireless measurements based on Bluetooth wireless protocol that can be used with existing sensors is proposed. The method finds application in condition monitoring and fault diagnosis of industrial machin-

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ery. A review of various condition monitoring methods used for fault diagnosis of transformers is presented in Ref. [10]. It is shown that partial discharge detection method can provide timely and complementary information with respect to other methods commonly in use, helping utility operators to plan maintenance actions. A work on on-line condition monitoring system has been presented in Ref. [11] for fault diagnosis of high voltage substations. Another example of a recent work on condition monitoring is the use of a dielectric spectroscopy method for condition monitoring of low voltage cables in nuclear power plant [12]. In a much earlier work [13], the comparison of several methods for condition monitoring of compressors has been provided. A study on the bearings of different internal clearances was performed by Ref. [14]. Their work shows that the motor current signature analysis could not detect bearing outer race defects with normal internal clearances.

Many methods have been developed which support the development of condition monitoring system using specialized and expensive sensors [15-25]. It is necessary to explore on a more effective and less costly method and this study focus on the condition monitoring of induction motors via non-invasive instantaneous power analysis (IPA) method.

This paper first presents the issues in condition monitoring of induction motors and thus Sec. 2 gives an overview of condition monitoring methods and the faults types as related to motor bearing. Sec. 3 presents the theory of the proposed non-invasive on-line condition monitoring system and gives the mathematical formulation associated to motor bearing faults. Sec. 4 presents the experimental set-up along with implementation of the proposed method on diagnosing of the normally occurred bearing faults. Finally Sec. 5 gives the conclusion of this paper.

2. Faults in induction motor

As induction motors are often symmetrical, hence faults normally disturb the symmetry of the motors. In most cases, reduced efficiency, unbalanced air gap voltages and line currents, increased space harmonics, decreased shaft torque, increased torque pulsation and increased losses are the usual symptoms related to the disturbed symmetry. The other factors which would contribute to burning of motors are thermal overloading, overloading due to undesirable stresses, air gap eccentricity, speed oscillations, stator winding failure, broken rotor bars, bearing failures and unbalanced voltages [2, 27, 28]. According to a survey in 2005 by the Electric Power Research Institute more than 40% burning of alternating current (AC) motors are due to failure of bearing [28, 29].

Bearing are made up of an inner and an outer race that assist in the motor shaft rotations. Several rolling elements (Balls) are placed in between the two races supported by a cage to keep the balls moving at equal distance from each other. Stresses developed in the motor causes fatigue in the bearing races that could cause localized defects (Single point defects like flaking or spalling or holes) and distributed defects (Multiple holes, surface roughness). Other factors that contribute to bearing malfunctions are improper lubrication, contamination, improper installation, corrosion and brinelling [2]. The defect in the bearing element produces the vibration at the characteristic defect frequencies which is related to the motor's speed and bearing dimensions. Bearing failures can also occur due to high bearing temperature. The increase in the winding temperature, improper lubrication, uneven distributions of temperature within the motor and the operating speed of the motor contribute for the rise of the bearing temperature. Consequently, the bearing temperature can give useful data to estimate the health of the bearing as well as health of the motor [19, 20].

The sensor based methods like vibration analysis, acoustic emission, noise analysis, chemical analysis and temperature measurements have been applied to protect motors from faults [21-25]. However sensors that form the integral part of these techniques are too expensive and require hardware access to the machine, and involve special expertise for proper installation. As every type of defect has its own unique characteristic defect frequencies, an analytical technique could be devised to provide the signature of the frequency modulations from the spectrum of the motor's current and voltage.

The earlier work on condition monitoring via the stator current monitoring technique have been reported for example in Refs. [25-29]. A more recent work through spectral analysis and instantaneous current signals to improve the detection at incipient bearing faults have been reported in Refs. [25, 26], whilst the use of noise filtration to tackle the effects of environmental noise on stator current spectrum have been proposed in Refs. [27, 33, 34]. A system for the online diagnosis of bearing faults equipped with a digital signal processing (DSP) board for signal processing at high-speed via statistical signal processing method that enhance the capability of the fault diagnosis has been proposed in Ref. [35]. In a similar work, Ref. [37] suggests the use of stator current and efficiency of the motors to find faults in bearing. Later, Refs. [40, 44] propose a technique that use torque frequency contents which can be observed in the stator current spectrum. The reviews on the condition monitoring techniques for the induction motors as reported in Refs. [46-48] indicates that motor current stator analysis is the most suitable non-invasive and economical method for the detection of the motor defects.

In most applications, current and voltage transformers are installed as part of the electrical protection system. It has been given in Refs. [33-38] that the mechanical vibrations are related to the stator current components at the specific characteristic frequencies. Any increased in the mechanical vibrations of the motor would increase the motor current due to the modulation of the air gap by the mechanical vibration. The impact of this modulation appears in the inductance of the stator and finally in the motor stator current. It is a non-invasive method and could be implemented at some distances away from the place where a motor is installed. Although the motor current stator analysis proves to be non-intrusive and economical for motor bearing fault detection, however, the change in amplitude values of the current signals are difficult to detect especially at no-load conditions [35-43]. As related to this, the instantaneous power analysis (IPA) method has been used to detect rotor, eccentricity and torque related defects at no-load and full-load conditions and at incipient stages, see for examples [2, 48-50]. The analysis of current and power signals were done in Ref. [51] to investigate the rotor defects in wind turbine induction generators. The usage of IPA method for analysis of bearing defects in induction motors has not being investigated and this paper addresses this new approach for analysis of various bearing defects.

It is essential to have a non-invasive on-line condition monitoring scheme which would have the ability to detect the bearing defects at incipient stages and under various loading conditions [30-42]. This work, in common with Ref. [44] is evaluating stator current using FFT spectrum. However, this study proposes an approach to condition monitoring of motors via intelligent diagnostic system based on IPA, and requires no special sensors for the measurements. This technique provides continuous real-time tracking of faults and estimates the severity through visual indication. In this matter, the focus of this paper is to reduce the motor failures due to bearing defects via non-invasive instantaneous power analysis method. This paper attempts to address on how the information from the voltage and current measurements can be used to detect defects in bearing of the motor, and how effective the IPA spectrum can be applied in a diagnostic condition monitoring system.

3. Non invasive on-line condition monitoring system

Since bearing are used to support the rotor during rotation, hence any defect in bearing will affect the radial movement of rotor. Due to this radial movement, air gap between rotor and stator will change to cause magnetic flux variations. Under ideal conditions, the instantaneous power of the motor can be calculated using Eq. (1) [2].

$$Po(t)=V_0(t)I_0(t)\,. \qquad (1)$$

where

$P_O(t)$, the ideal instantaneous power

$V_0(t)$, the ideal instantaneous supply voltage

$I_0(t)$, the ideal un-modulated motor stator current.

However, the presence of defect disturbs the symmetry of flux between stator and rotor which creates modulation (Oscillation) in stator current which could be observed at specific frequencies. The modulated motor current can be calculated using Eq. (2) [48, 50]. Under these conditions, the instantaneous power can be calculated using Eq. (3).

Table 1. Expected inner race defect frequencies under various loading conditions.

Motor speed (rpm)	Load condition	$m=1$		$m=2$	
		LSB (Hz)	USB (Hz)	LSB (Hz)	USB (Hz)
1497	No load	139.5	339.5	379	579
1395	Full load	128	328	356	556

$$I(t)=I_0(t)+mI_0(t)\cos\left[2\pi\left(f_e \pm f_v\right)t-\alpha_0\right]. \qquad (2)$$

$$P(t) = Po(t) + mV_0(t)I(t)[cos\left\{4\pi(f_e - f_v)t - \alpha_0 - \frac{\pi}{6}\right\} + cos\left\{4\pi(f_e + f_v)t - \alpha_0 - \frac{\pi}{6}\right\} + 2\,cos\left(\alpha_0 - \frac{\pi}{6}\right) cos(2\pi f_v t)] \qquad (3)$$

where

f_e , is the electric supply frequency

f_v , is the vibration frequency due to defect in any component of the bearing

α_0 is the load angle of the motor

m, is the modulation index

f_{if} , is the bearing inner race defects frequency

f_{0f} , is the bearing outer race defects frequency

f_{bd} , is the bearing ball defects frequency

and, $f_v = f_{if}, f_{of}, f_{bd}$.

Eqs. (2) and (3) reveal that the defects inside the motor create modulations (oscillations) in the stator current which could be observed as two sideband components, $(f_e \pm f_v)$. In contrast, three modulations related frequency components appeared in instantaneous power equation, i.e., the two are at $(2f_e - f_v)$ and $(2f_e + f_v)$, and one appears directly at the vibration frequency, f_v . The amplitude of these sideband components are amplified due to supply voltage, explaining why the motor instantaneous power carries more information related to fault as compared to stator current. The defects in bearing cause sinusoidal modulations in the instantaneous power signal that reveals the harmonic (Defect) frequencies in the power spectrum. The location of these harmonic frequencies allows the identification of abnormalities in the bearing. The term "m" represents the modulation index of these sinusoidal modulations in which, m = 1 refers to1st order harmonic (Vibration) frequency, and etc.

3.1 Calculation of characteristic defect frequencies for bearing inner race defects

The holes of various sizes are induced in the inner race of the bearing to create artificial defects. The characteristic defect frequency (f_{es}) related to bearing inner race defects is calculated using Eqs. (4)-(6) and are shown in Table 1.

$$f_{es} = \left|2f_e \pm 2mf_{if}\right| \qquad (4)$$

Table 2. Expected outer race defect frequencies under various loading conditions.

Motor speed (rpm)	Load condition	m = 1		m = 2	
		LSB (Hz)	USB (Hz)	LSB (Hz)	USB (Hz)
1497	No load	59.68	259.6	219.3	419.3
1395	Full load	48.80	248.8	197.6	397.6

Table 3. Expected ball defect frequencies under various loading conditions.

Motor speed (rpm)	Load condition	m = 1		m = 2	
		LSB (Hz)	USB (Hz)	LSB (Hz)	USB (Hz)
1497	No load	95.9	295.9	291.87	491.8
1395	Full load	86.5	286.5	273	573

$$f_{if} = 0.6 N_b f_r \tag{5}$$

$$f_r = \frac{f_e}{P}(1-s) \tag{6}$$

where

f_{es} , is the characteristic defect frequency

N_b , is the number of balls inside the bearing

f_r , is the rotor frequency in Hz

s, is the slip of the motor

s = 0.002 for no load condition of the motor

s = 0.007 for full load condition of the motor

P, is the number of pole pairs of the motor.

3.2 Calculation of characteristic defect frequencies for bearing outer race defects

The holes of various sizes are induced in the outer race of the bearing to create artificial defects. The characteristic defect frequency (f_{es}) related to bearing outer race defects is calculated using Eqs. (7)-(9) and are shown in Table 2.

$$f_{es} = \left| 2 f_e \pm 2 m f_{of} \right| \tag{7}$$

$$f_{of} = 0.4 N_b f_r \tag{8}$$

$$f_r = \frac{f_e}{P}(1-s). \tag{9}$$

3.3 Calculation of characteristic defect frequencies for bearing ball defects

The defects are created artificially (man-made) on the ball bearing using an electric discharge machine (EDM). The characteristic defect frequency (f_{es}) related to bearing ball defects is calculated using Eqs. (10) and (11) and are shown in Table 3.

$$f_{es} = \left| 2 f_e \pm 2 m f_{bd} \right| \tag{10}$$

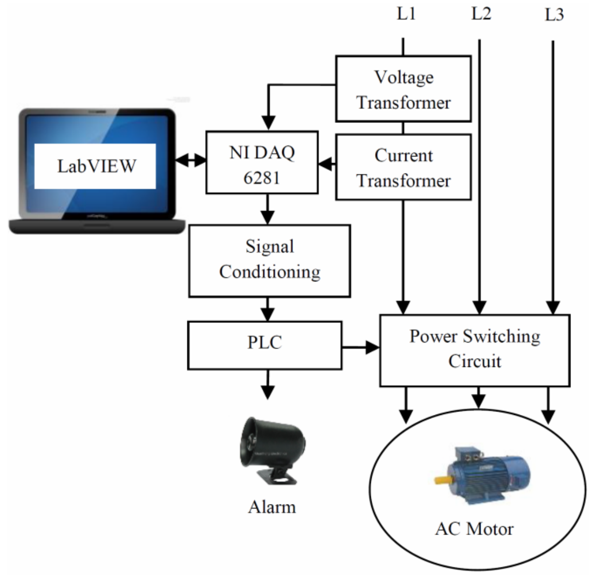


Fig. 1. Block diagram of the developed experimental test rig.

$$f_{bd} = \frac{D_c}{D_b} f_r \left(1 - \frac{D_b^2}{D_c^2} \cos^2 \alpha \right) \tag{11}$$

where

D_b , is the ball diameter (6 mm)

D_c , is the pitch diameter of bearing (25 mm)

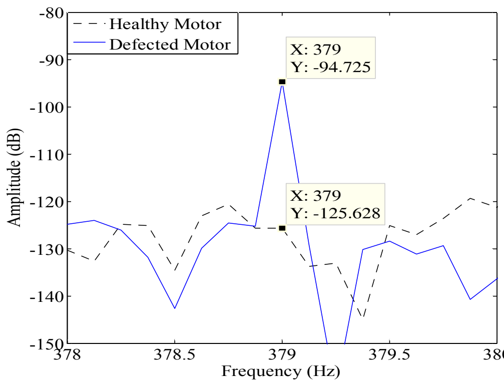
α, is the ball contact angle (Zero degree).

4. Results and analysis

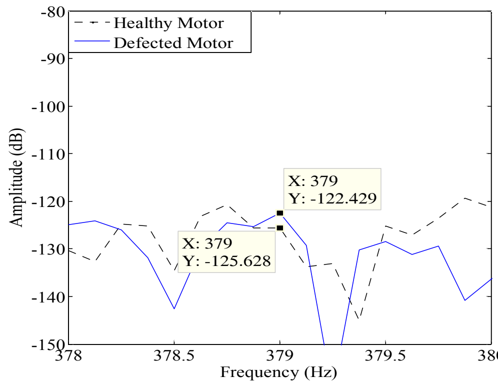
An overview of the development of experimental test rig for the intelligent diagnostic condition monitoring system is presented briefly. The rig has been designed using the commonly available firm-wares in industry i.e. induction motor, Hall-effect current sensor, voltage sensor (AC input/AC output type), and a programmable logic controller (PLC), The National Instrument data acquisition (NI DAQ) module is interfaced with LabVIEW® software to acquire and process the current and voltage measurements to calculate the FFT spectrum. A 4-pole, 50 Hz, 0.5 HP machine is used as the test motor, operated at a nominal speed of 1395 rpm. The NI DAQ 6281 has the following specifications: Number of analog inputs: 16, Analog input range: ±10 Volts, Max scan rate: 625kS/s, resolution: 18 bits, Number of analog outputs: 2, Analog output range: ± 10 Volts, and analog output resolution: 16 bits, Total number of samples: 240 kS, Scan rate: 30 kHz, scan mode: continuous, terminal configuration: Differential, Window: Hanning, and the Frequency resolution: 0.125 Hz. The block diagram of the experimental test rig is shown in Fig. 1. The ball bearing installed on the motor shaft has the pitch diameter (D_c) of 25 mm. Each bearing contains 8 balls with diameter (D_b) of 6 mm. The bearing consists of four parts namely, inner race, outer race, rolling elements (Balls) and cage. The contact angle of the ball with the race (α) is

Table 4. Summary of change in amplitude values at various inner race defect levels.

Inner race defect size (mm)	Characteristic inner race defect frequency (Hz)		Change in dB	
	No load	Full load	No load	Full load
1	379	356	3	6
2	379	356	7	13
3	379	356	17	28
4	379	356	31	54



(a)

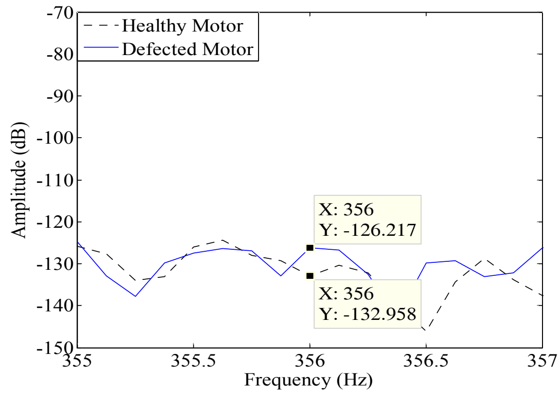


(b)

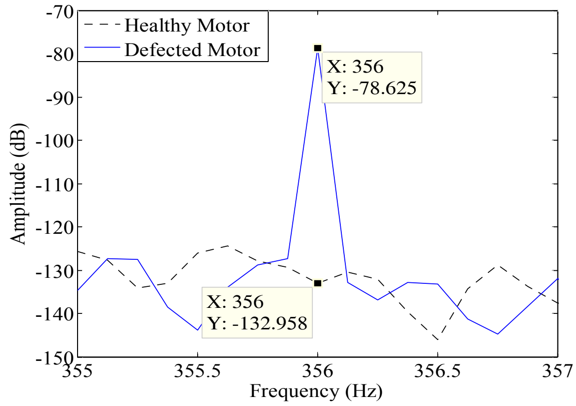
Fig. 2. The spectrum of the healthy and defected motor under no-load condition at 379 Hz for inner race defects of (a) 1 mm; (b) 4 mm.

Table 5. Amplitude values for bearing inner race defects based on types of analysis.

Defect size (mm)	Type of analysis			
	Stator current analysis (dB)		Instantaneous power analysis (dB)	
	No load	Full load	No load	Full load
2	-77	-74	-118	-119
4	-74	-68	-94	-78



(a)



(b)

Fig. 3. The spectrum of the healthy and defected motor under full-load condition at 356 Hz for inner race defects of (a) 1 mm; (b) 4 mm.

assumed to be zero degrees.

The majority of breakdowns of the motors are due to defects in the bearing, therefore the detail diagnostic of faults associated to bearing races and balls defect via the proposed technique are the emphasis of this analysis.

4.1 Case study 1: analysis of bearing inner race defects

A total of eight tests have been conducted under no-load and full-load conditions. The IPA spectrum (Product of instantaneous voltage and instantaneous current of the motor) of the healthy and defected motor for both conditions are shown in Figs. 2 and 3, respectively. The dotted line indicates the frequency spectrum for the healthy motor, while the solid line for the defected motor. It is observed from the frequency spectrum that for defected motor under the no-load condition the change in amplitude value at the characteristic defect frequency is very small fora 1mm defect size as compared to a 4 mm defect size. For full-load condition, the change in amplitude increases much larger values. The analysis of frequency spectrum for inner race defect sizes (of 1, 2, 3 and 4 mm) is summarized in Table 4.

The results in Table 4 imply that as the bearing inner race defects size is increased the amplitude values at characteristic defect frequencies also increases. In this context, the increased in the amplitude values is more prominent at the full-load.

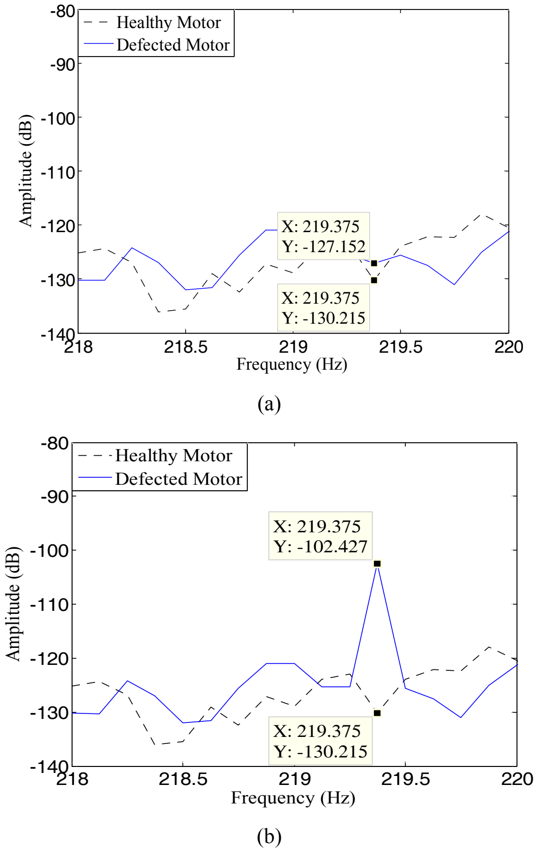


Fig. 4. The spectrum of the healthy and defected motor under no-load condition at 219.375 Hz for outer race defect of (a) 1 mm; (b) 4 mm.

In Table 5 are given the type of analysis with comparisons made to the inner race defects. At no-load, the difference that occurs in amplitude values from 2 mm defect size to 4 mm defect size is 3 dB for the stator current analysis scheme and 24 dB for the instantaneous power analysis scheme. Interestingly, at full-load the change in amplitude values is 6 dB for the stator current analysis but 41 dB for the IPA scheme. The IPA method provides stronger fault frequencies related components implying that it is a better option for the diagnosis of the inner race defects.

4.2 Case study 2: analysis of bearing outer race defects

A total of eight tests have been conducted to study the outer race defects. The IPA spectrums for the healthy and defected motor are shown in Figs. 4 and 5, respectively. The dotted line indicates the spectrum of healthy motor, while the solid line indicates otherwise. For a 1 mm defect size under no-load, the change in amplitude value at the specific characteristic defect frequency is very small, however the change is more significant at a 4 mm defect size. At full-load, there is a significant change in amplitude values that increases much larger values for a much larger defect size. The analysis of frequency spectrum for the outer race defect sizes (of 1, 2, 3 and 4 mm) is

Table 6. Summary of change in amplitude values at various outer race defect.

Outer race defect size (mm)	Characteristic outer race defect frequency (Hz)		Change in dB	
	No load	Full load	No load	Full load
1	219.375	197.625	3	5
2	219.375	197.625	7	11
3	219.375	197.625	15	26
4	219.375	197.625	28	51

Table 7. Amplitude values for bearing outer race defects based on types of analysis.

Defect size (mm)	Type of analysis			
	Stator current analysis (dB)		Instantaneous power analysis (dB)	
	No load	Full load	No load	Full load
2	-73	-73	-123	-110
4	-70	-69	-102	-70

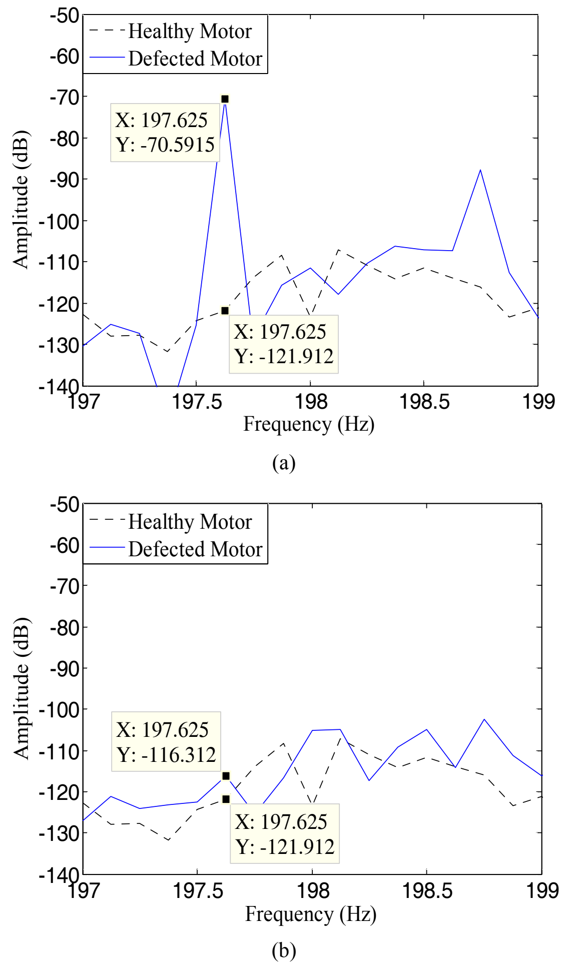


Fig. 5. The spectrum of the healthy and defected motor under full-load condition at 197.625 Hz for outer race defect of (a) 1 mm; (b) 4 mm.

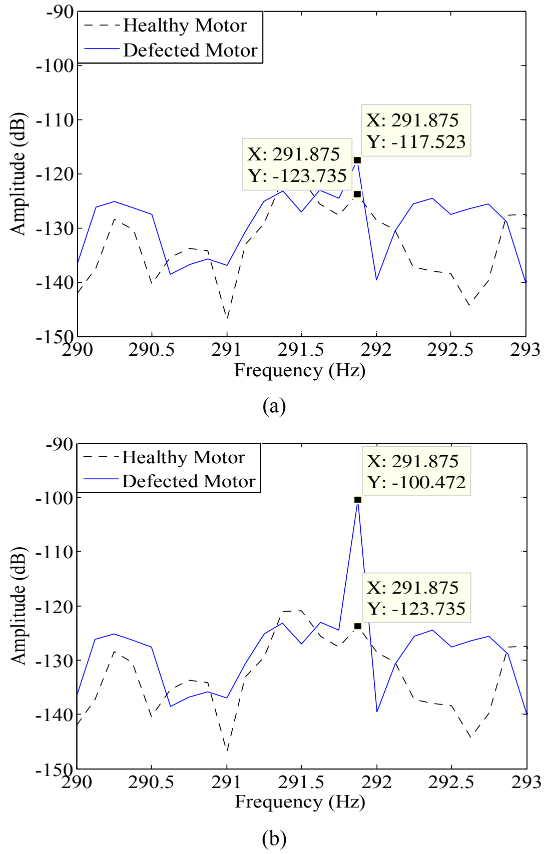


Fig. 6. The spectrum of the healthy and defected motor under no-load condition at 291.875 Hz for (a) one ball defects; (b) three balls defect.

summarized in Table 6. As the outer race defect size is increased the amplitude values at characteristic defect frequencies also increases. Notably, the increased is more prominent at the full-load condition. The results of the IPA scheme as compared to the stator current analysis scheme are shown in Table 7. It is observed that for no-load condition, the difference that occurs in amplitude values from the 2 mm defect size to the 4 mm defect size is 3 dB for the stator current analysis scheme and 21 dB for the IPA scheme. Likewise, for full-load condition, the change in amplitude values is 4 dB for the stator current analysis scheme and 40 dB for the IPA scheme. The IPA scheme is shown to strengthen the fault frequencies and therefore is more suitable for the diagnosis of the bearing outer race defects.

4.3 Case study 3: analysis of bearing ball defects

A total of six tests have been conducted at different defect levels (1 to 3 balls damaged). In Figs. 6 and 7 the dotted line indicates the frequency spectrum for healthy motor whilst the solid line indicates otherwise. One can analyzes that for the defected motor at no-load with one ball defects the change in amplitude at specific characteristic defect frequency is much smaller as compared to when having three balls defect. At full-load, there is a significant change in amplitude values at one ball defects as well as at three balls defect. In Table 8 are given the characteristic frequency and change in dB for the respective ball defects. In this perspective, the increase in amplitude values is more prominent at full-load as compared to during no-load condition. Still under both conditions the change in amplitude value at characteristic defect frequencies increases corresponding to the levels of severity of the defects.

Table 8. Summary of change in amplitude values of ball defect frequencies at various defect levels.

Number of damaged balls	Characteristic ball defect frequency (Hz)		Change of dB	
	No load	Full load	No load	Full load
1	291.875	273	6	8
2	291.875	273	13	19
3	291.875	273	23	34

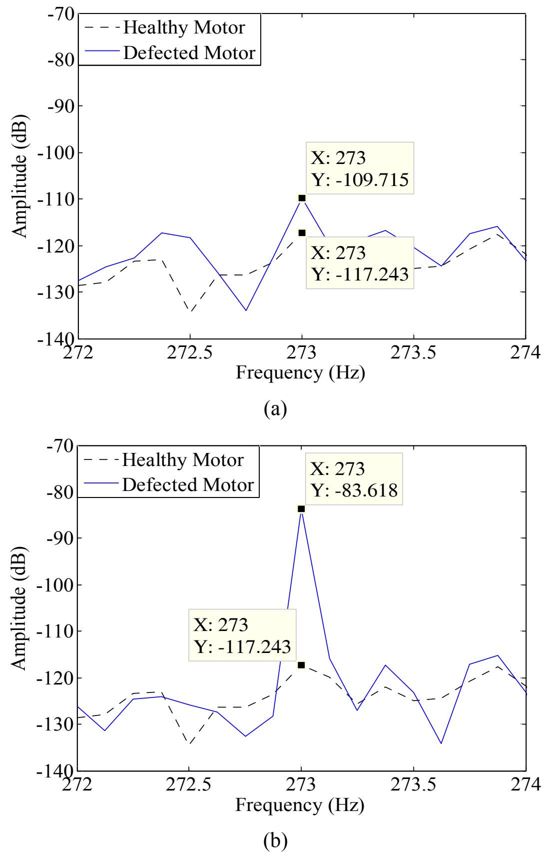


Fig. 7. The spectrum of the healthy and defected motor under full-load condition at 273 Hz for (a) one ball defects; (b) three balls defect.

5. Conclusions

This work proposes a non-invasive fault diagnosis system of induction motors via a more effective scheme for use especially in severe environment where access to a motor is not easy. The proposed system that possesses features like continuous real-time monitoring as well as providing the information on severity of faults would pave way to the development of an automatic decision making. Experimental investigations of inner race, outer race and ball defects of the bearing at the no-load and full-load conditions are conducted and the instantaneous power spectrums associated to the faults are studied. The results confirm the viability of this approach. It could be foreseen that this would enhance the reliability and accuracy of the methods used for the on-line detection and diagnosis of motor bearing faults at incipient stages employing the analysis of the instantaneous power spectrum.

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