Effectiveness of vibration monitoring in the health assessment of induction motor

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Abstract

Induction motors are widely used prime movers for rotating machinery in most of the industrial applications. Reliability of the induction motors plays a significant role in reduction in downtime of the machinery. Proper diagnostic procedures are to be followed to assess the condition of the motor. Based on the literature, it is found that the vibration analysis is mostly used for diagnosis of rotating systems. However, industrial experiences reveal that potential motor failures have been observed very frequently even with proper vibration based condition monitoring. Therefore, this paper focuses on further investigations of whether the vibration monitoring stand alone can properly diagnose the presence of faults such as eccentricity in an induction motor or any other alternative technique should be employed in addition to the vibration monitoring for better diagnosis. In this paper, experimental investigations have been carried out to monitor the changes in the vibration and current spectrum of an eccentric motor in its decoupled and coupled state with a healthy rotor system.

1. Introduction

Condition monitoring techniques have been successfully used by many industries to diagnose and identify the causes of machinery failures at incipient stages of their development so as to plan adequate maintenance actions at appropriate time. Condition monitoring comprises as diagnostics and prognostics. Diagnostics deals with fault detection, fault identification and fault isolation while prognostics deals with fault prediction and evaluation of remaining useful life of machinery. Industrial machinery generally consists of a prime-mover and the main system. Electric AC motors are generally used as prime movers in industry. Many review papers on condition monitoring of the rotating machinery and induction motors are present in the literature (Jardine, A. K. S., Lin, D., & Banjevic, D. 2006; Mehrjou, M. R., Mariun, N., Hamiruce Marhaban, M., & Misron, N. 2011). Common faults observed in rotating machinery are unbalance, misalignment, looseness, bearing failures, shaft bents, soft-foot, etc (Sinha, J. K., & Elbhbah, K. 2013).

Many techniques such as vibration analysis (Tandon, N. 1994), acoustic emission analysis (Germen, E., Başaran, M., & Fidan, M. 2014), wear and oil analysis (Loutas, T. H., Roulias, D., Pauly, E., & Kostopoulos, V. 2011), motor-current signature analysis (Acosta, G. G., Verucchi, C. J., & Gelso, E. R. 2006; Didier, G., Ternisien, E., Caspary, O., & Razik, H. 2007; MA Cruz, AJ Marques Cardoso, S. 2000), infrared thermography technique (Bagavathiappan, S., Lahiri, B. B., Saravanan, T., Philip, J., & Jayakumar, T. 2013) etc have been used for fault detection of the above stated faults through condition monitoring of the rotating machinery. Nowadays, use of non-invasive condition based maintenance diagnosis techniques are becoming an essential requirement of the industries (Thorsen, O. V., & Dalva, M. 1995). This enables the maintenance personnel to reduce the machine downtimes and also allows them to take necessary actions before the occurrence of actual failures.

Motor current signature analysis (MCSA) is a widely used non-invasive technique like vibration monitoring for fault detection in electric drives. The MCSA is a non invasive online monitoring technique which is used for detecting various faults like broken rotor bar, eccentricity, bearing, misalignment and shorted turn (Benbouzid, M. E. H., & Kliman, G. B. 2003; Verma, A. K., Sarangi, S., & Kolekar, M. H. 2014). Depending upon its nature of fault signal i.e. stationary or non stationary, MCSA uses various fault detection techniques like Fast Fourier Transformation (FFT) analysis, Instantaneous power FFT, bi-spectrum analysis, wavelet analysis, park vector approach. Mostly motor current Fourier analysis is used for the detection of steady

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state fault conditions and wavelet analysis is used for transient fault state conditions. This paper focuses on the experimental investigations on the changes due to coupling and decoupling on the motor's signatures. The rest of the paper is organised as follows. Air-gap eccentricity in the induction motor and the methods for its diagnosis is presented in section 2, followed by the experimental set-up and test procedure in section 3. Section 4 deals with the results and discussions of the experimental investigations of the obtained signatures at fore-mentioned states for three different speeds, along with their estimated similarity levels. Conclusions and references are presented in the last two sections.

2. AIR – GAP ECCENTRICITY

Induction motors are widely used prime- movers for various industry applications. Many industries have successfully implemented health monitoring of rotating machinery. It has been found that proper diagnosis of the motors is also required to avoid unforeseen downtime due to faults in the induction motors. Faults in an induction motors may be due to either electrical or mechanical sources. Electrically induced faults are inter-turn faults, single phasing, insulation damage, short-circuit, fluctuations in power supply etc. Mechanical related faults for induction motors are rotor broken bars, rotor eccentricity, bearing faults, bent rotor shaft, cracked shaft, soft-foot, looseness etc.

Eccentricity occurs due to the non-uniform distribution of air-gap between the stator and rotor in the motor (Barbour, A., & Thomson, W. T. 1997). Eccentricity is classified as static, dynamic or mixed type. Air-gap eccentricity is one of the faults inherited in the induction motor even with good control over manufacturing tolerances. Normally, eccentricity within (5-10) % is considered as healthy (Barbour, A., & Thomson, W. T. 1997). As presented in the literature eccentricity can be studied either by observing the sidebands with respect to rotor slot frequency (Eq.1) or at supply frequency (Eq.2) (Barbour, A., & Thomson, W. T. 1997; El Hachemi Benbouzid, M. 2000; Obaid, R. R., & Habetler, T. G. 2003).

$$f_{ecc} = f_s\left[\left(R \pm n_d\right)\left(\frac{1-s}{p}\right) \pm n_{ws}\right] \qquad (1)$$

where, f_{ecc} : frequency components which are functions of air-gap eccentricity.

f_s : supply frequency,

R : no. of rotor slots,

n_d : 0 for static and 1 for dynamic,

s : slip,

p : no. of pole pairs and n_{ws} : 1,3,5,7.

$$f_{ecc} = f_s\left[1 \pm m\left(\frac{1-s}{p}\right)\right] \qquad (2)$$

where, m : 1,2,3,.....(any integer).

Nandi, S., Toliyat, H. A., & Li, X. (2005) proposed that eccentricity in vibration spectrum can be detected at

$$f_v = \left(f \pm 2 f_{sb}\right) \qquad (3)$$

where, f : rotational frequency, f_{sb} : side-band frequency around rotational frequency.

Model based approaches have been proposed to detect air-gap eccentricity considering the asymmetrical distribution of the winding slots in an induction motor (Toliyat, H. A., Arefeen, M. S., & Parlos, A. G. 1996; Finley, W. R., Hodowanec, M. M., & Holter, W. G. 1999; Liang, B., Payne, B. S., Ball, A. D., & Iwnicki, S. D. 2002; Holopainen, T. P., Tenhunen, A., & Arkkio, A. 2005). Similarly a space vector angular fluctuation method is used to detect bearing faults and misalignment in motor is presented (Arkan, M., Çaliş, H., & Tağluk, M. E. 2005) and a fuzzy inference model (Bae, H., Kim, Y. T., Lee, S. H., Kim, S., & Lee, M. H. 2005) is proposed by using Fourier and wavelet analysis of stator current for broken rotor bar detection. Discrete Wavelet Transformation (DWT) technique is used to understand the behaviour of induction motor in the presence of dynamic eccentricity (Antonino-Daviu, J., Jover, P., Riera, M., Arkkio, A., & Roger-Folch, J. 2007). An index is proposed based on recorded torque with respect to time solved by time series data mining technique (Ebrahimi, B. M., Etemadrezaei, M., & Faiz, J. 2011). Recently, a mathematical model has been presented to study the mixed air gap eccentricity in an induction motor by calculating the severity of static and dynamic eccentricity at different load conditions (Maruthi, G. S., & Hegde, V. 2013) at supply frequency as presented in (Eq. 4 & 5)

$$\%SF_{DE} = \left(\frac{Average\_magnitude\_of\,(f_s \pm f_r)}{magnitude\_of\,(f_s)} \times 100\right) \qquad (4)$$

$$\%SF_{SE} = \left(\frac{Average\_magnitude\_of\,(f_s \pm 2 f_r)}{magnitude\_of\,(f_s)} \times 100\right) \qquad (5)$$

where, $\% SF_{SE}$: severity of static eccentricity.

$\% SF_{DE}$: severity of dynamic eccentricity.

f_s : supply frequency.

f_{sb} : side-band frequency.

3. EXPERIMENTAL SET-UP AND TEST PROCEDURE

Experimental set-up consists of a Spectra-quest make machine fault simulator (MFS) used to conduct the experimental study. MFS consists of three phase 1hp induction motor coupled to a single rotor system through variable frequency drive (see **Figure 1a**). Integrated circuit piezoelectric (ICP) accelerometers and clamp meters are the sensors used for the collection of signatures from induction motor (see **Figure 1b and 1c**). A four channel OROS-OR34 DAQ system was used for data collection and analysis.

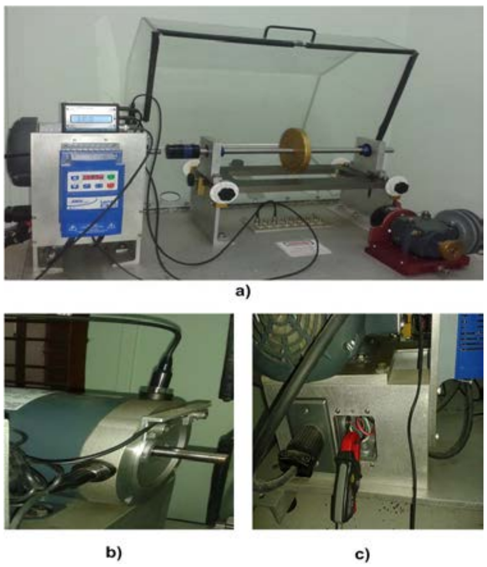

Figure 1. a) Experimental test set-up b) ICP accelerometers c) Current clamp-meter.

Vibration signatures from the motor at drive-end bearing were acquired in both the horizontal and vertical radial directions. Motor current signature was also collected using a clamp meter. The experiment was conducted at 50 Hz, 55 Hz and 60 Hz supply frequencies through variable frequency drive (VFD) at 4096Samples/sec and the average spectrum signatures were collected for the following cases:

a. Rotor system decoupled from motor

b. Rotor system coupled to motor

4. RESULTS AND DISCUSSIONS

4.1. Spectral Analysis

We observed the vibration spectrums of decoupled and coupled motor at drive end in horizontal and vertical radial directions along with the motor current spectrum. Spectrums for both the states of the motor are analyzed to observe whether there is effect of the coupling and decoupling of the motor on its signatures.

In the decoupled state, a strong peak at '2*f*' compared to '1*f*' in the frequency-domain of the vibration spectrums in both the radial directions (see left column of **Figures 2a, 2b, 3a, 3b and 4a, 4b**) are present. Side-bands around 'f' is clearly visible in the vibration spectrum of radial vertical direction and side-bands around 'f_s' in the current spectrum of the motor in decoupled state at all the three frequencies (see left column of **Figures 2c, 3c and 4c**). In radial horizontal direction, side-bands around 'f'is partially visible at all the three frequencies (see left column of **Figures 2a, 3a and 4a**). However, at '$2f$' the side-bands are clearly visible in both the radial directions at 55Hz, 60Hz but is partially visible at 50Hz. But at all the three frequencies 'dB' level at '$2f$' are more than that at 'f' which clearly indicates the motor eccentricity (Finley et al. 1999).

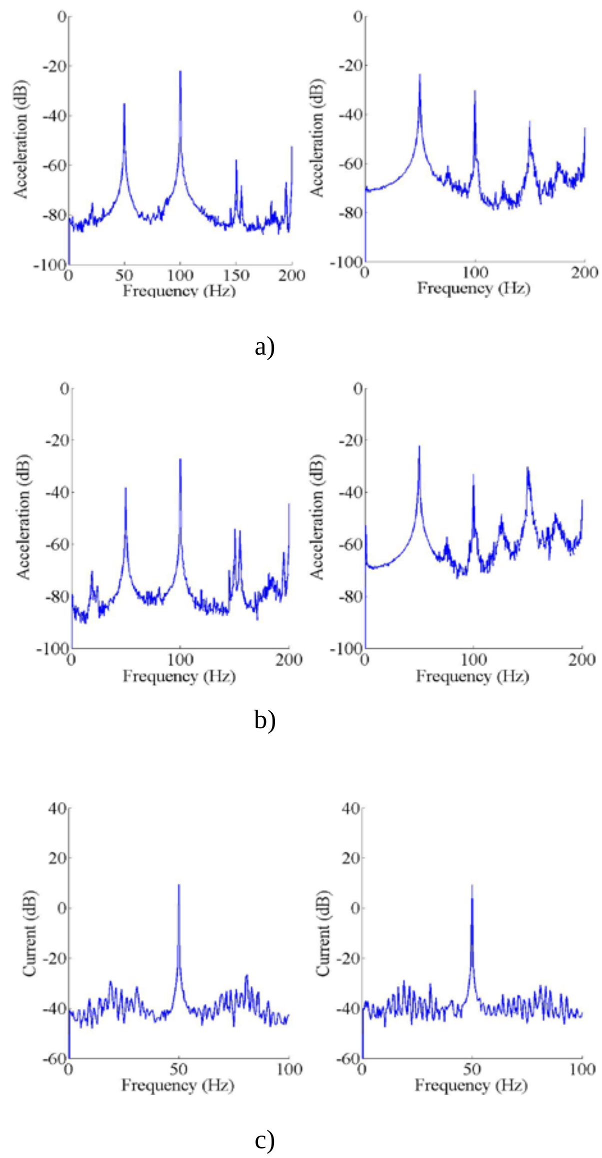

Figure 2. 'dB' plot of a) Horizontal vibration b) Vertical vibration c) current spectrums of motor in decoupled state (left column) and coupled state (right column) at 50Hz.

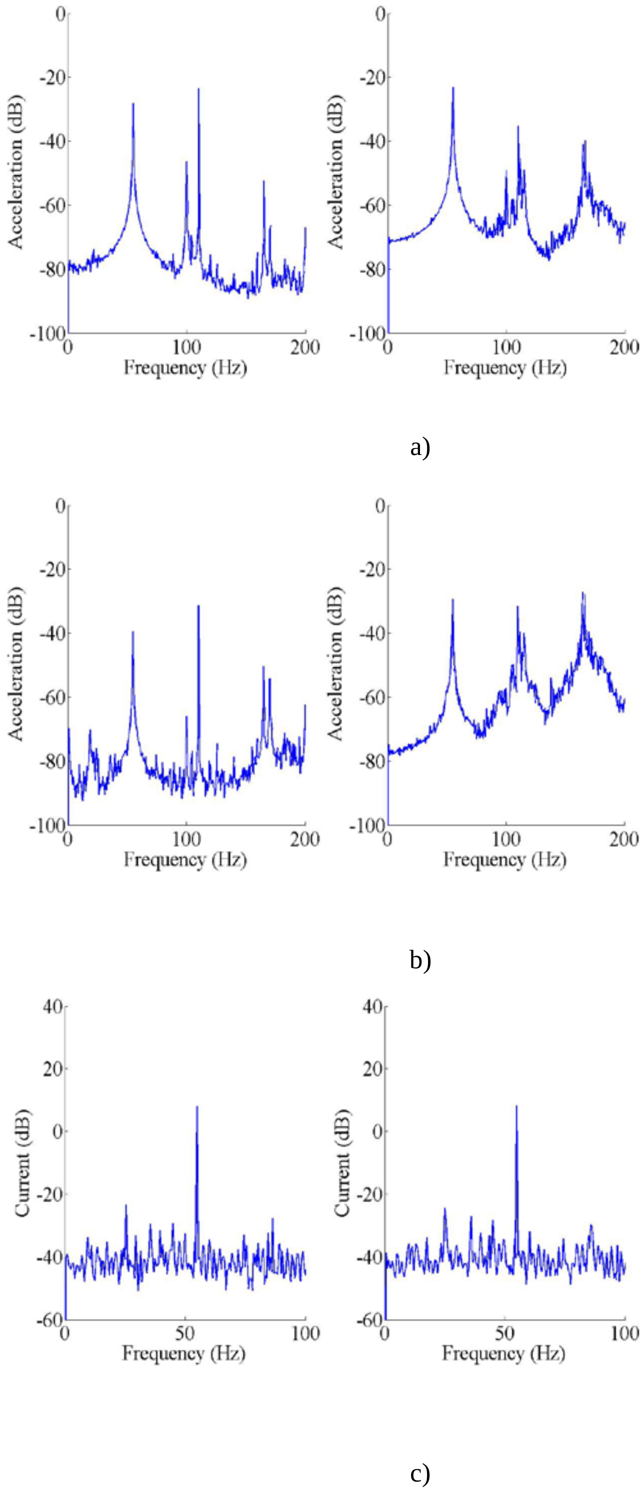

Figure 3. ‘dB’ plot of a) Horizontal vibration b) Vertical vibration c) current spectrums of motor in decoupled state (left column) and coupled state (right column) at 55Hz.

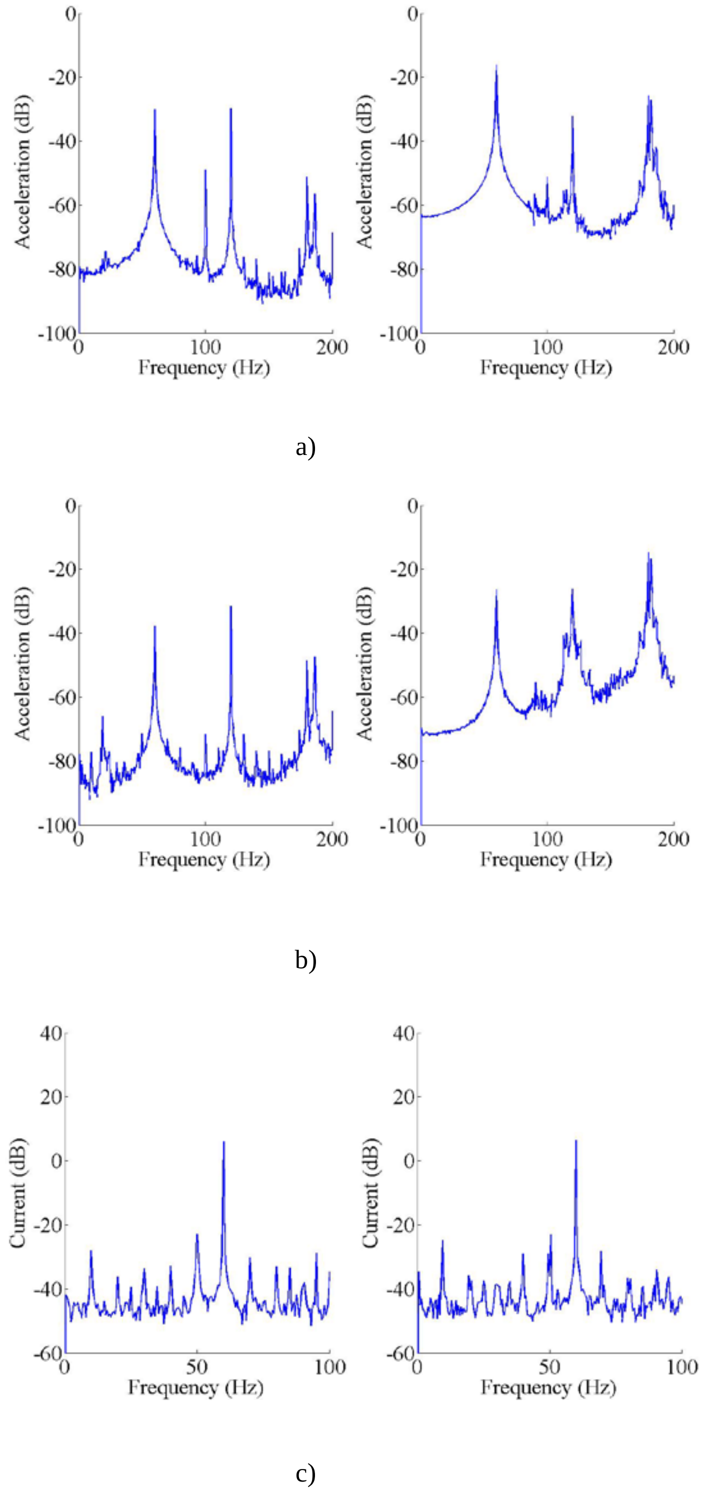

Figure 4. ‘dB’ plot of a) Horizontal vibration b) Vertical vibration c) current spectrums of motor in decoupled state (left column) and coupled state (right column) at 60Hz.

In the coupled state, in both the horizontal and vertical radial directions amplitude at '1*f*' compared to '2*f*' is observed (see right column of **Figures 2a, 2b, 3a, 3b and 4a, 4b**). When motor is coupled to the rotor system, side-bands around the rotational frequency ' *f* ' are not visible in vibration 'dB' spectrum at all the three speeds in both the radial directions. However, similar side-bands with little rise in peak levels are observed in current 'dB' spectrum to that of decoupled state (see right column of **Figures 2c, 3c and 4c**).

With the increase in the magnitude of the side band peaks, the dB difference between 'f_s' and side-band peaks further decreases below 42 dB indicating the presence of fault in the motor (Maruthi, G. S., & Hegde, V. 2013). As the speed increases the number of peaks entering the fault zone (i.e. difference < 42 dB) also increases. Results for all the three supply frequencies are presented in **Table 1 &Table 2** (see **Appendix A**).

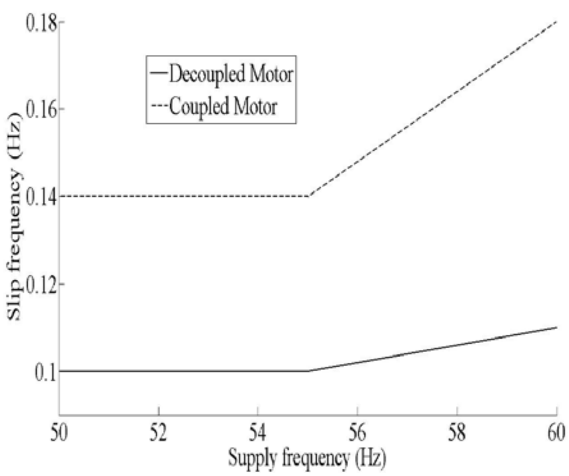

Figure 5. Supply Frequency vs Slip Frequency

In the coupled state, side-bands around ' *2f* ' in vibration spectrum are clearly visible at all the three frequencies in both the radial directions and the 'dB' level of ' *2f* ' is comparable to that of ' *f* '.This, clearly indicates motor eccentricity. From the above observations, it is clear that significant changes have been observed in the radial vibration signatures when compared to the current signatures of the motor in decoupling and coupling of the rotor system. The effect of the eccentricity on the slip of the motor for both the states is shown in **Figure 5**. It is observed that slip frequency in both the states of the motor is same upto the 55Hz and major difference is observed there- after in the coupled state of the motor. Next sub-section deals with the clustering analysis, to check the similarity of the signatures in both coupled and decoupled states of the motor.

4.2 Hierarchal Clustering Analysis

Unsupervised learning procedures are mainly classified into non- hierarchical clustering and hierarchical clustering techniques. Many times, the data has clusters which have sub-clusters and sub sub-clusters and so on. Hierarchical clustering sequence is a method that clusters two samples into the same group based on their similarity level 'k' that remains together at all higher levels. The most natural representation of a hierarchical clustering is a corresponding tree called as Dendrogram (Duda, R. O., Hart, P. E., & Stork, D. G. 1999).

In this paper, hierarchical variable clustering analysis is used to check the similarity level of vibration and current spectrums (upto 15^{th} harmonic of supply frequency) of the motor for both coupled and decoupled states using MINITAB16 software. Variable clustering analysis is carried using 'single' linkage method based on absolute correlation distance between the respective spectrums of coupled and decoupled states of the motor. Similarity level in the case of horizontal direction is about 55.4% while running at 50Hz then increased to 64.69% at 55Hz and thereby reduced to 61.8% at 60Hz. In the case of vertical direction it is only around 49.5% at 50Hz and decrease in similarity level is observed with further increase in speed to 38.64% at 55Hz and to 24.53% at 60Hz. It can be concluded that the similarity level between the vibration signatures of both coupled and decoupled state of motor in the horizontal radial direction is more than that of vertical radial direction.

Similarity level of current spectrum for both coupled and decoupled states of motor is above 98% at all the three supply frequencies considered in the experiment. It has also been observed that the similarity level in current spectrum partially changes *w.r.t* the supply frequency from 99.66% at 50Hz to 98.39% at 60Hz (see **Figure 6**).

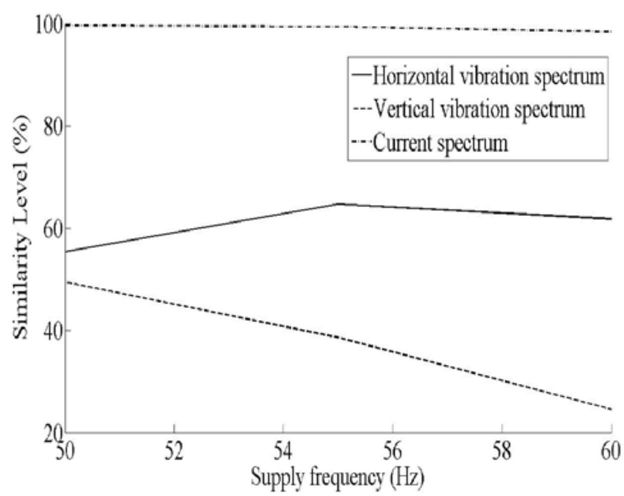

Figure 6. Supply Frequency *vs* Similarity Level

This clearly indicates the effectiveness of MCSA technique over vibration analysis for fault detection of induction motor even when it is coupled with its rotor.

5. CONCLUSION

The focus of this paper is on the need of a proper health monitoring system for assessment of the operational condition of industrial prime-movers such as an induction motor. It is found in the present experimental study that even though vibration monitoring is an effective method for health assessment of rotating machines, including electric motors, it is not capable of identifying eccentricity fault in the electric motors when it is coupled to the rotating system. Vibration monitoring of electric motors is found to be effective only if the data is collected after it is decoupled from the rotating system. As in industrial cases, it is not practical to implement such data collection methods as it leads to the additional shut-down of the system and requirement of the additional spares for decoupling. Vibration monitoring is not able to effectively detect air-gap eccentricity of motor in the coupling state. The present study has shown that monitoring by motor current signature analysis is very effective and efficient tool for diagnosing air-gap eccentricity in the decoupled and coupled state of the motor with equivalent similarity levels. Therefore, this paper suggests that a combination of MCSA and vibration monitoring will be more effective for the whole driver and driven system in proper fault diagnosis without any additional shutdown.

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APPENDIX: A

State of the motor		Side-band Frequencies	Vibration spectrum from Accelerometers						Current Spectrum from Clamp meter		
			Radial Horizontal Direction			Radial Vertical Direction					
Decoupled	Supply Frequency (Hz)	f_s	50Hz	55Hz	60Hz	50Hz	55Hz	60Hz	50Hz	55Hz	60Hz
	Side-band Frequencies (Hz)	(f_s+f_r, f_s-f_r)	(80.5,21)	-	-	(81,19)	(60,49)	(70,50)	(81,19)	(60,50)	(70,50)
		(f_s+2f_r, f_s-2f_r)	-	-	-	-	(65.5,45)	(80,40)	-	(64.5,45)	(80,40)
		(f_s+3f_r, f_s-3f_r)	-	-	-	-	-	(90,30)	-	-	(90.5,30)
		(f_s+4f_r, f_s-4f_r)	-	-	-	-	(74.5,24)	(100,19)	-	(74.5,35.5)	(100,20)
		(f_s+5f_r, f_s-5f_r)	-	-	-	-	-	(110,10)	-	-	(110,10)
		(f_s+6f_r, f_s-6f_r)	-	-	-	-	(86.5,36)	-	-	(86.5,24)	-
Coupled	Supply Frequency (Hz)	f_s	50Hz	55Hz	60Hz	50Hz	55Hz	60Hz	50Hz	55Hz	60Hz
	Side-band Frequencies (Hz)	(f_s+f_r, f_s-f_r)	-	-	-	-	-	-	(81,19)	(60.5,49.5)	(69.5,50.5)
		(f_s+2f_r, f_s-2f_r)	-	-	-	-	-	-	-	(64,45)	(79.5,40)
		(f_s+3f_r, f_s-3f_r)	-	-	-	-	-	-	-	-	(90.5,30)
		(f_s+4f_r, f_s-4f_r)	-	-	-	-	-	-	-	(74.5,40)	(101,19.5)
		(f_s+5f_r, f_s-5f_r)	-	-	-	-	-	-	-	-	(111,9.5)
		(f_s+6f_r, f_s-6f_r)	-	-	-	-	-	-	-	(85,25)	-

Table 1. Observed sideband peaks in fault zone (≤ 42 dB)

		Magnitude of side-band frequency in radial vertical vibration at supply frequency (dB)		
	f_s	50 Hz	55 Hz	60 Hz
		-38.27	-39.41	-37.72
Side-band Frequency (Hz)	(f_s+f_r, f_s-f_r)	(-76.42, -70.31)	(-74.15,-76.54)	(-72.92,-71.47)
	(f_s+2f_r, f_s-2f_r)	Not Visible	(-78.56,-79.49)	(-75.92,-84.12)
Severity (%)	$\%SF_{SE}$	-	49.87 %	47.13 %
	$\% SF_{DE}$	52.16 %	52.44 %	52.24 %

Table 2. Severity in dynamic and static eccentricity.

BIOGRAPHIES

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