ASHISH KUMAR SINHA
SUKANTA DAS
and
TARUN KUMAR CHATTERJEE

# A case study of bearing fault monitoring techniques for induction motors

*Research has witnessed considerable advancement in the field of fault detection and monitoring in induction motors. The advent of on-line and automated systems for fault diagnosis has added a new dimension in the area of condition monitoring of induction motors. So keeping in mind the vast scope of this field of research and the economic impact that bearing failures have on industries, a review of different techniques used for bearing fault detection is done by compiling various available literatures.In this paper the different bearing fault detection methodologies are grouped according to the techniques used for bearing fault detection. The advantages and disadvantages associated with the fault detection schemes are also reported. The review illustrates that bearing fault detection is primarily done using Fourier transform based analysis and/or Wavelet transform based tools by analyzing vibration signals and/or motor current signals. The vibration signals have proved to be the superior option pertaining to the various advantages as discussed in the literature. The objective of the present work is to unfold a broad area of the updated status of the bearing fault monitoring and will assist future researchers to realize the scope of research in this area at a glimpse.*

***Keywords:*** *Condition monitoring; induction motors; bearing faults; current signal; vibration signal; fourier transform; wavelet transform.*

## I. Introduction

The practice of fault detection is as primitive as the advent of the machines themselves. Initially, protection of any machinery depended on the various relays to ensure reliable operation. But with the gradual reduction in the man-machine interface, the need for on-line condition monitoring is at the zenith so as to curb the faults at their very inception. An effective fault diagnosis technique helps in reducing unscheduled downtime considerably and minimizing the financial losses.

Messrs. Ashish Kumar Sinha, Dept. of Mining Machinery Engineering, Sukanta Das, Dept. of Electrical Engineering and Tarun Kumar Chatterjee, Dept. of Mining Machinery Engineering, Indian School of Mines, Dhanbad 826004, India. Email: sinha.1990@gmail.com; asksukanta@rediffmail.com; tkcism@yahoo.com

The major faults associated with the electrical machines include [1]:

1. Winding faults,
2. Broken rotor bars,
3. Air-gap irregularity related faults, and
4. Bearing failures.

In general, stator winding breakdown causes about 30% - 40% of induction motor (IM) failures. A survey carried out by IEEE and Electric Power Research Institute reports that the stator faults are responsible for 37% of the machine failures[2]. A separate report as published by the General Electric, under the sponsorship of Electrical Power Research Institute and the IEEE industry applications society illustrates that bearing problems cause over 40% of total machine failures [3], [4]. The studies done in [5-9] report that bearing failures account for about 45-50% of total machine failure. The possibility of occurrence of different faults that occur in an IM as reported by [10] is shown in Fig.1. Over the years various parameters have been analyzed to understand the symptoms for the detection of faults. These parameters mainly include noise measurement, temperature measurement, vibration monitoring, current signature analysis, axial flux measurement, chemical analysis, infrared and radio frequency monitoring, artificial intelligence (AI) and neural network etc. [1], [11].

This paper aims to compile various literatures of bearing fault monitoring techniques. The next section deals with the

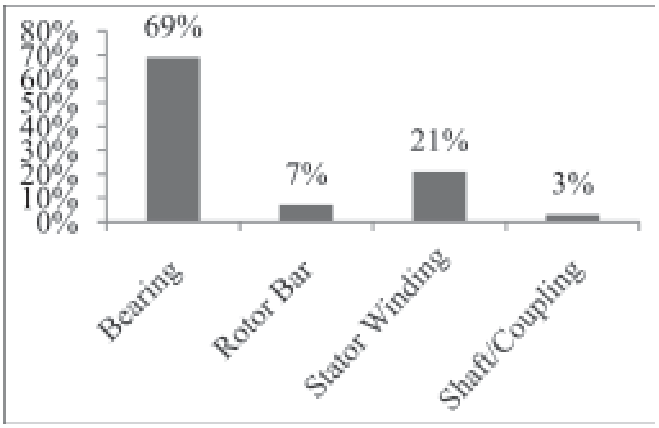


Fig.1 Percentage contribution of various faults in IM [10]

types of bearing damages along with the general parameters and methods used for their detection. Section III deals with the different monitoring techniques used for the detection of bearing faults in IM. Finally, Section IV concludes the work.

## II. Types of bearing damages, their causes, effects and parameters used for detection

Bearing damages may occur due to both internal and external operating stresses. Internal operating stresses may be caused by vibration, pre-existing eccentricity and bearing currents due to solid state drives [12]. Apart from these, the various external causes that contribute in bearing damages include contamination and corrosion, improper lubrication (both over and under lubrication) and improper installation of the bearing [1]. Sometimes bearing damages are marked as rotor asymmetry faults which fall under the category of eccentricity related faults [13]. This eccentricity occurs due to the misalignment of rotor during installation. This results in variation in the air-gap flux density thus causing variation in stator current spectra. Ball bearing related faults are categorized as outer bearing race defects, inner bearing race defects, ball defects and train defects [1]. The vibration frequencies can be used to detect all these types of bearing failures. These frequencies under different faults are given as [1]:

$$f_v\,[\mathrm{Hz}] = \left(\frac{N}{2}\right) f_r \left[1 - b_d \cos(\beta)/d_P\right]$$

for outer bearing race defect, ... ... (1)

$$f_v\,[\mathrm{Hz}] = \left(\frac{N}{2}\right) f_r \left[1 + b_d \cos(\beta)/d_P\right]$$

for inner bearing race defect, ... ... (2)

$$f_v\,[\mathrm{Hz}] = \frac{d_P f_r}{2b_d}\{1 - \left[b_d \cos(\beta)/d_P\right]^2\}$$

for a ball defect, and ... ... (3)

$$f_v\,[\mathrm{Hz}] = \frac{f_r}{2}\left[1 - b_d \cos(\beta)/d_P\right]$$

for train defect ... ... (4)

where, $f_r$ is the rotational frequency, $N$ is the number of balls, $b_d$ and $d_P$ are the ball diameter and ball pitch diameter respectively, and $\beta$ is the angle of contact of the ball with the races. The ball bearing dimensions are shown in Fig.2.

It is seen from (1)-(4) that specific information about machine construction is required to calculate exact race frequencies. However, these frequencies can be approximated to the following equations for most of the bearings with six to twelve balls:

$$f_o = 0.4nf_r$$ ... ... (5)

$$f_i = 0.6nf_r$$ ... ... (6)

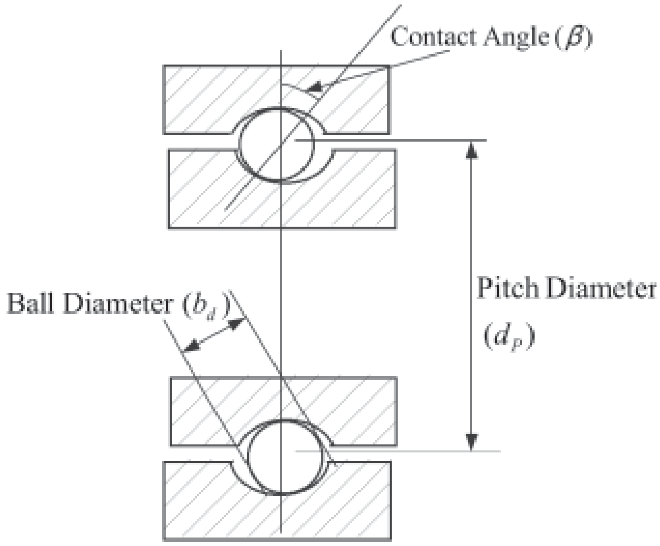


Fig.2 Ball bearing dimensions [28]

where, is the mechanical rotor speed in hertz, $f_o$ is the outer race frequency, $f_i$ is the inner race frequency and $n$ is the number of bearing balls.

Bearing faults also exhibit characteristic frequencies in the current spectrum. Bearing fault frequencies of the vibration spectrum and the current spectrum are interrelated [14]. The relation between current fault frequencies and bearing fault frequencies for the corresponding bearing fault is given as,

$$f_{bng} = |f_1 \pm mf_v|$$ ... ... (7)

where, $m$ = 1,2,3,…..and $f_v$ is one of the characteristic vibration frequencies. This relationship between the bearing vibration and the stator current spectrum exist because of the anomalies in the air-gap flux density produced by air-gap eccentricity [15]. The mechanical displacement due to bearing damage causes variation in the air-gap of the machine similar to a combination of rotating eccentricities moving in both clockwise and counter-clockwise directions [16]. The work also establishes that as the fault worsens, vibration signals used for bearing fault detection are affected by the machine speed.

Bearing faults are also categorized as (1) single point roughness, which is visible on the raceways, rolling elements etc. and gives rise to characteristic fault frequencies in the vibration spectrum, and (2) generalized roughness. The latter refers to bearings with no visible defects and thus these do not produce any characteristic fault frequency spectrum. Single point roughness is caused by defects which include spalling, brinelling, corrosion, and electric discharge. Furthermore, generalized roughness is caused by deformed rolling element or deformed or wrapped raceways [17], [18]. Usually fatigues relating to bearing failures begin with small fissures which are located at the lower surfaces of the races and rolling elements. These fissures propagate gradually and generate detectable noises and vibrations. The fragments of the material break loose further thus producing a localized fatigue phenomenon known as flaking or spalling [18].

Mainly vibration and current are used as parameters to diagnose and monitor bearing faults and their severity [19-21]. Vibration based method is internationally standardized in the industry using ISO 10816 standard [22]. Both of these parameters have their own advantages and disadvantages. Vibration analysis has the drawback of installation of vibration sensors in many practical cases, especially the ones involving large number of electrical machines. Whereas, in the case of current spectrum monitoring, it is difficult to distinguish bearing fault signatures from non-fault component or noise present in the stator current spectrum [23]. The study done in [24] proposed that stator current monitoring is more feasible as it can produce results at-par with the vibration monitoring scheme but does not require access to the motor. Vibration and current signals are used as inputs to pre-processors. These pre-processors use various techniques based on Fourier transform (FT) and Wavelet transform (WT) for fault detection. These techniques have been discussed in detail in the next section.

## III. Monitoring techniques used for bearing fault detection

As discussed in the previous section, both current and vibration analysis are used for bearing fault detection. These parameters are used as input to a pre-processor for the execution of fault detection algorithm. The preprocessor uses different techniques for fault detection. Initially, Fast Fourier Transform (FFT) was used for bearing fault detection. The fault detection technique has gradually evolved to Discrete Wavelet Transform (DWT) [25].

### A. Fourier transform based technique

Motor current signature analysis (MCSA) and vibration analysis uses FFT as the pre-processor for fault detection and analysis. This approach is advantageous due to its computational simplicity but it simultaneously deals with the drawback of non-applicability on non-stationary signals [26]. Moreover, FFT is unable to give time information about the spectrum analysis. So pin-pointing of fault is not possible using only FFT technique. The experimental analysis carried out in [27] compares the applicability of FFT on current as well as on vibration signals for the diagnosis of all types of bearing defects. The tests set up uses a 6205 standard bearing having 10 balls and operating at a no-load speed of 1708 rotations/min. The supply frequency is 60 Hz. Moreover, the FFT spectrum corresponding to the different bearing related faults is shown by Fig.3. Fig.3(a) shows the FFT spectrum diagram of machine vibration and current signal. Similarly, Fig.3(b) depicts the FFT spectrum for bearings with inner race defects. Likewise, Fig.3(c) and 3(d) show the FFT spectrum of machine vibration and current signals for bearings having ball defect and train defect respectively. Furthermore, the numerical validation of the experimentally obtained fault frequencies is done using the mathematical relations reported in the literature. The details of the numerical values of fault frequencies pertaining to vibration analysis and current analysis along with the equations used for numerical validation are tabulated in Table I.

The corresponding fault frequency components have larger magnitude when the machine vibration is monitored as compared to MCSA. Moreover, the fault frequencies in the current spectrum generally get suppressed by the neighboring frequencies and the higher order fault frequency components are of lesser magnitude. This establishes the fact that when FT based technique is used the vibration monitoring gives better results as compared to current monitoring.

Fault detection of MB ER-10K ball bearings having 8 balls, ball diameter of 0.3125 inch and pitch diameter of 1.319 inch is presented in [28]. The tests were carried out at different rotating frequencies of 10, 20 and 30 Hz and the corresponding fault frequencies were both numerically calculated and experimentally verified. The numerical values of the bearing fault frequencies for different values of rotational speed are enlisted in Table II.

The FFT spectrum diagram showing the experimentally verified numerical values of bearing fault frequencies for 10 Hz rotational speed is given in Fig.4. The changing values of fault frequencies further establishes the fact that magnitude

Table I Fault frequencies using vibration analysis and MCSA for different bearing failures of 6205 ball bearing [27]

| Type of bearing fault | Equation used for calculating vibration spectrum fault frequency | Equation used for calculating current spectrum fault frequency | Numerically calculated vibration spectrum fault frequency (Hz) | Numerically calculated current spectrum fault frequency (Hz) |
|---|---|---|---|---|
| Outer race defect | Equation 1 | Equation 7 | 107.4 | 47.4 & 167.4 for m=1<br>134.8 & 254.8 for m=2 |
| Inner race defect | Equation 2 | Equation 7 | 167.3 | 107.3 & 227.3 for m=1<br>284.6 & 384.6 for m=2 |
| Ball defect | Equation 3 | Equation 7 | 70.5 | 10.5 & 30.5 for m=1<br>81 & 201 for m=2 |
| Train defect | Equation 4 | Equation 7 | 18 | 42 & 78 for m=1<br>24 & 96 for m=2 |

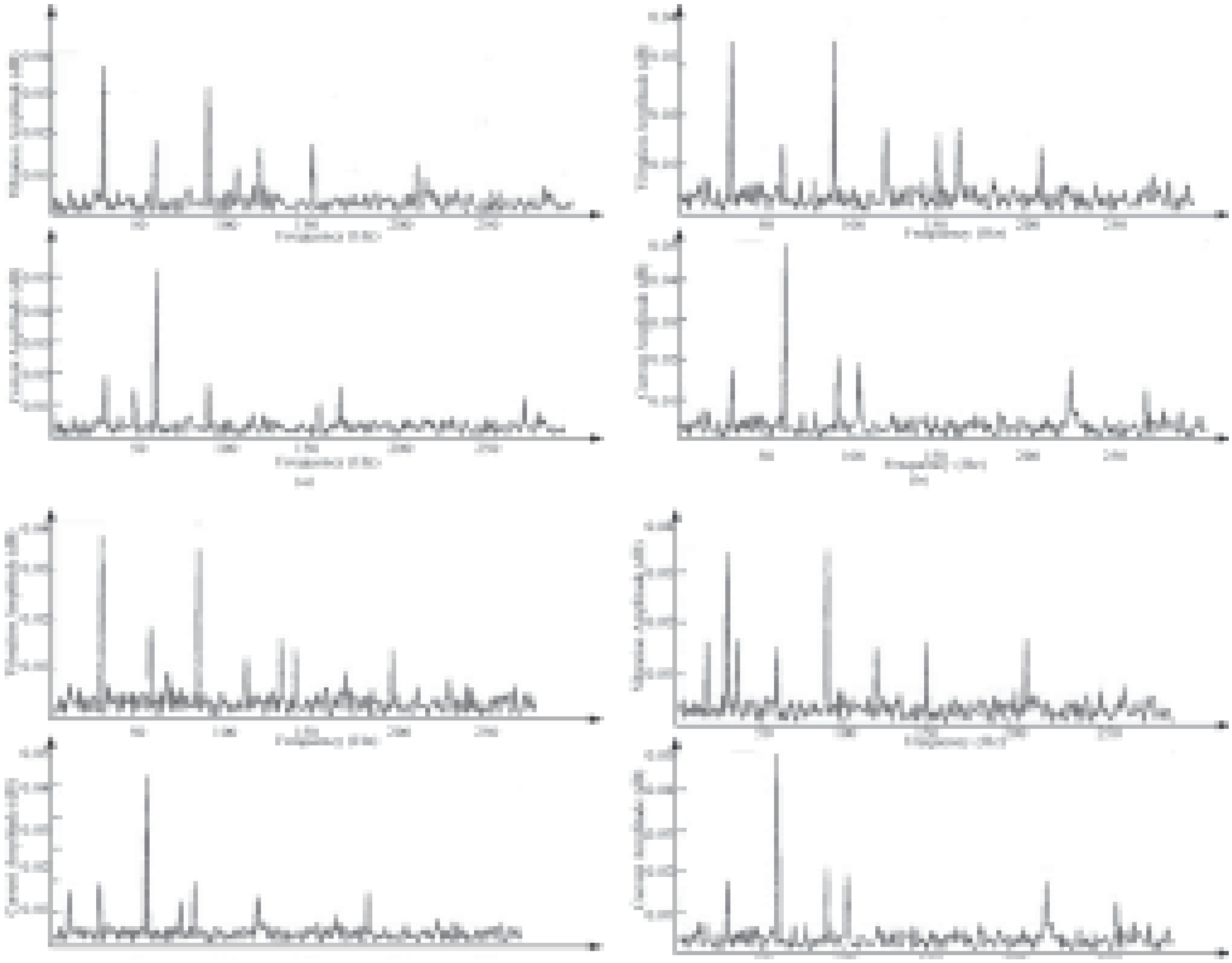

Fig.3 Frequency spectrum of captured current and vibration data of a motor with faulty bearing having (a) outer race fault, (b) inner race fault, (c) ball defect and (d) train defect of a 6205 ball bearing [27]

TABLE II FAULT FREQUENCIES OF MB ER-10K BALL BEARING AT DIFFERENT ROTATIONAL SPEEDS USING VIBRATION SPECTRUM [28]

| Type of bearing fault | Equation used for calculating vibration spectrum fault frequency | Fault frequency multiplier | Fault frequency for rotational speed of 10 Hz (Hz) | Fault frequency for rotational speed of 20 Hz (Hz) | Fault frequency for rotational speed of 30 Hz (Hz) |
|---|---|---|---|---|---|
| Outer race defect | Equation 1 | 3.052 | 30.52 | 61.04 | 91.56 |
| Inner race defect | Equation 2 | 4.948 | 49.48 | 98.96 | 148.44 |
| Ball defect | Equation 3 | 1.992 | 19.92 | 39.84 | 59.76 |
| Train defect | Equation 4 | 0.3815 | 3.815 | 7.63 | 11.445 |

of bearing faults frequencies are directly dependent on the rotational speed of the motor.

The fact that machine vibration analysis is superior to current signature analysis is also validated in [23]. This work also concludes that performance of the same bearing in different installations is not comparable. Furthermore, in connection with the comparison of vibration and current monitoring for bearing fault detection, Trajin et al proposed a vibration spectral energy detector and an automatic detector based on current spectral energy estimation to diagnose bearing faults [29]. These detectors have certain limitations like in case of a variable supply frequency the stator current spectral indicator can be used for fault detection but when the machine is running at a constant speed then only vibration analysis can be used. Apart from this, experimental analysis has shown that vibrational spectral energy indicator is more sensitive as compared to the stator current spectral indicator. The fault indicators in this study are compared to

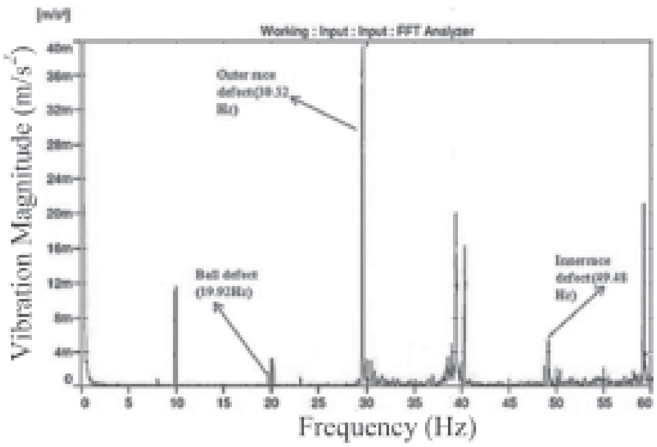


Fig.4 Vibration spectrum of bearing fault frequencies at a rotational speed of 10 Hz of a MB ER-10K ball bearing [28]

the scalar indicators. For a discrete signal $x$, three major scalar indicators such as the *Crest Factor,* the *K* factor and the *Kurtosis* [30] are defined as

$$Crest\ Factor = \frac{\max(|x|)}{\sqrt{\frac{\sum_{i=1}^{N} x_i^{\,2}}{N}}} \qquad \dots \dots (8)$$

$$K = \max(|x|)\sqrt{\frac{\sum_{i=1}^{N} x_i^{\,2}}{N}} \qquad \dots \dots (9)$$

$$Kurtosis = \frac{(1/N)\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^4}{\left[(1/N)\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2\right]^2} \qquad \dots \dots (10)$$

The growth in indicates the presence of a bearing fault. Whereas and have to be compared to the respective thresholds in order to diagnose the presence of a fault.

Another model developed by Immovilli et al. in 2013 used externally induced vibration for the simulation of bearing defects [31]. The kinematic model designed in this study is shown in Fig.5. As per the diagram, during downward and upward movement of the shaft, the equivalent stiffness becomes equal to andrespectively. Under no fault condition.

It is evident from the reported studies that FT based techniques have mainly been concentrated on the spectral analysis of machine vibration and motor current. It has been experimentally and analytically proved in the studies that vibration monitoring gives more accurate results as compared to current monitoring. This leads us to the conclusion that vibration monitoring is better than current monitoring for bearing fault detection and diagnosis.

### B. Wavelet transform based techniques

WT is used to overcome the drawbacks associated with the FT based technique i.e. non-applicability to non-

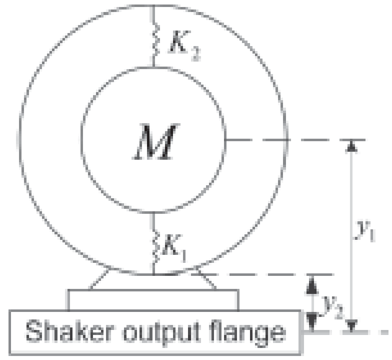


Fig.5 Kinematic model of bearing stiffness [31]

stationary signals and resolution problems. WT uses a 'variable window function' for different values of frequency and time to solve the resolution problem [32]. The width of the window is chosen in such a way that the signal corresponding to that window can be assumed to be stationary in nature. WT decomposes a time domain signal into a number of frequency groups thus providing a very efficient alternative to Short Time Fourier Transform for the analysis of non-stationary signals [33]. The frequency separation using WT is shown in Fig.6. WT has another advantage that it can be used for analyzing a signal in transient state which cannot be done using FT.

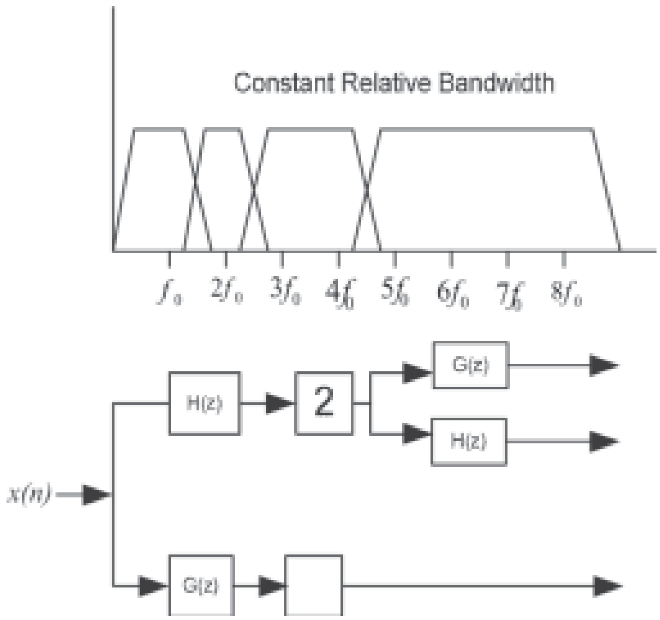


Fig.6 Frequency separation using wavelet decomposition [27].

Literature survey shows that the process of bearing damage detection using WT has mainly been concentrated on the analysis of motor current. Vibration monitoring using WT still remains a relatively unexplored zone. In 2001 L. Eren et al proposed a wavelet based technique for bearing damage detection by analyzing the starting current transient of an IM [34]. In this study the starting current transient of an induction motor has been analyzed using DWT to diagnose bearing fault. Furthermore, the frequency sub bands before and after the fault are compared to analyze the effect of fault frequencies when the motor starts. The authors in [35] proposed a WT based technique for the isolation and identification of dry bearing faults in induction machine. In this study, raw data obtained from physical machine parameters for isolation and identification of dry bearing faults is treated. Different families of WT have been introduced and implemented with vibration signals. Mexican Hat Wavelet is seen to give most satisfactory results. It has also been concluded in the study that WT cannot detect multiple faults at a time. But WT and FT together can be used effectively to extract information about the condition of the machine.

Therefore, the reported studies of bearing fault detection using WT leads us to conclude that the process of bearing fault detection is mainly concentrated on current signature analysis. It is already established in the literature that vibration spectrum is more accurate as compared to MCSA. Thereby, using WT vibration spectrum is likely to yield way better results than the ones already available. Literature survey also reveals that multiple faults cannot be detected using WT. This is mainly because faults like bearing damage and rotor bar damage have very similar spectrums. So to differentiate between the vibration spectrums, motor has to be switched off and if the vibration still persists then it is an indication of the presence of bearing faults. Literature survey also suggests that a combined use of WT and FT will give accurate results and will aid in the process of fault pin-pointing.

## IV. Conclusions

A detailed literature survey of bearing fault monitoring techniques leads to a number of conclusions. Firstly, it is evident from the available literature that current and vibration are predominantly used as inputs to the preprocessor for signature analysis. The monitoring techniques are mainly FT and WT based.

Literature on FT based analysis of motor current and machine vibration confirms that vibration monitoring is better than current monitoring for bearing fault detection and diagnosis. On the other hand, WT based analysis for bearing fault monitoring still remains relatively unexplored. The limited amount of study done in this regard is concentrated on the analysis of motor current. As established in the literature, vibration analysis is superior to MCSA; therefore, a large domain of bearing fault monitoring using WT based analysis of machine vibration remains unexplored. Another important finding from the literature survey is the incapability of WT to detect multiple faults at a time. This is because of the similar nature of the spectrum related to the respective faults.

Moreover, it is also proven that the use of either FT or WT alone is inadequate to carry out the process of bearing fault pin-pointing. Whereas, the combined use of FT and WT shall give very accurate results and will consequently aid in the pin-pointing of bearing fault.

The present work illustrates the relevant concepts, mathematical equations and results related to the traditional bearing fault monitoring techniques, taken from various publications of different authors.

## References


[1] Vas P., (1993): Parameter estimation condition monitoring and diagnosis of electrical machines. Oxford, U.K: Clarendon.

[2] M.R.W. Group, (1985): “Report of large motor reliability survey of industrial and commercial installations Part I and II,” *IEEE Transactions on Industry Application,* vol. IA-21, no. 4, pp. 853-872.

[3] P.F. Albrecht, J.C. Appiarius, R.M. McCoy, E.L. Owen, and Sharma D.K., (1986): “Assessment of the reliability of motors in utility applications-Updated,” *IEEE Transactions on Energy Conversion*, vol. EC-1, no. 1, pp. 39-46.

[4] I.M.R.W. Group, (1985): “Report of large motor reliability survey of industrial and commercial installations: Part I,” *IEEE Transactions on Industry Applications*, vol. IA-21, no. 4, pp. 853-864.

[5] I.M.R.W. Group, (1985): “Report of large motor reliability surveyof industrial and commercial installations-Part II,” *IEEE Transactions on Industry Applications*, vol. IA-21, no. 4, pp. 865-872,.

[6] I.M.R.W.Group, (1987): “Report of large motor reliability survey of industrial and commercial installations-Part III,” *IEEE Transactions on Industry Application*, vol. IA-23, no. 1, pp. 153-158.

[7] Thorsen O.V., and Dalva M., (1995): “A survey of faults on induction motors in offshore oil industry, petrochemical industry, gas terminals and oil refineries,” *IEEE Transactions on Industry Application*, vol. 31, no. 5, pp. 1186-1196.

[8] Nandi S., Toliyat H.A., and Xiaodong L., (2005): “Condition monitoring and fault diagnosisof electrical motors- A review,” *IEEE Transactions on Energy Conversion*, vol. 20, no. 4, pp. 719-729.

[9] Thorsen O.V., and Dalva M., (1999): “Failure identification and analysis for high-voltage induction motors in the petrochemical industry,” *IEEE Transactions on Industry Application*, vol. 35, no. 4, pp. 810-818.

[10] Bonnett A.H. and Yung C., (2008): “Increased efficiency versus increased reliability,” *IEEE Industry Applications Magazine*, vol. 14, no. 1, pp. 29-36.

[11] Kliman G.B., and Stein J., (1990): “Induction motor fault detection via passive current monitoring,” Proceedings of the International Conference on Electrical Machinery,

Cambridge, MA, pp. 13-17, August.

[12] Chen S., and Lipo T.A., (1998): "Bearing currents and shaft voltages of an induction motor under hard- and soft-switching inverter excitation," *IEEE Transactions on Industry Application*, vol. 34, no. 5, pp. 1042-1048.

[13] Grieger J., Supangat R., Ertugrul N., Soong W.L., Gray D.A., and Hansen C., (2006): "Estimation of static eccentricity severity in induction motors for on-line condition monitoring," Conference Record of the 2006 IEEE Industry Applications Conference, 41st IAS Annual Meeting, Tampa, FL, pp. 2312-2319, October.

[14] Schoen R.R., Habetler T.G., Kamran F., and Bartfield R.G., (1995): "Motor bearing damage detection using stator current monitoring," *IEEE Transactions on Industry Application*, vol. 31, no. 6, pp. 1274-1279.

[15] Schoen R.R., & Habetler T.G., (1993): "Effects of time-varying loads on rotor fault detection in induction machines," Conference Record of the 1993 IEEE Industry Applications Society Annual Meeting, Toronto, Ont, pp. 324-330, October.

[16] Stack J.R., Habetler T.G., and Harley R.G., (2003): "Effects of machine speed on the development and detection of rolling element bearing faults," IEEE Power Electronics Letters, vol. 1, no. 1, pp. 19-21.

[17] Stack J.R., Habetler T.G., and Harley R.G., (2003): "Fault classification and fault signature production for rolling element bearings in electric machines," IEEE Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives, Atlanta, GA, pp. 172-176, August.

[18] Eschmann P., Hasbargen L., and Weigand K., (1958): Ball and roller bearings: Their theory, design, and application, K.G. Hayden & Co., London, UK.

[19] Knight A.M., and Bertani S.P., (2005): "Mechanical fault detection in a medium-sized induction motor using stator current monitoring," *IEEE Transactions on Energy Conversion*, vol. 20, no. 4, pp. 753-760.

[20] Zhou W., Habetler T.G., and Harley R.G., (2007): "Bearing condition monitoring methods for electric machines: A general review," IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, (SDEMPED 2007), Cracow, Poland, pp. 3-6, September.

[21] Petty D.J., (1999): "Analysis of bearing vibration monitoring," IEE Colloquium on Understanding Your Condition Monitoring, Chester, pp. 4/1-4/11, April.

[22] The International Organization for Standardization, (2009): "Mechanical vibration-evaluation of machine vibration by measurement on non-rotating parts-part 3," Retrieved from ISO website https://www.iso.org/obp/ui/#iso:std:iso:10816:-3:ed-2:v1:en.

[23] Obaid R.R., Habetler T.G., and Stack J.R., (2003): "Stator current analysis for bearing damage detection in induction motors," Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, Atlanta, GA, USA, pp. 182-187, August.

[24] Kliman G.B., and Stein J., (1992): "Methods of motor current signature analysis," Electric Machines and Power Systems, vol. 20, no. 5, pp. 463-474.

[25] Rubini R., and Megenhetti U., (2001): "Application of the envelope and wavelet transform analyses for the diagnosis of incipient faults in ball bearings," Mechanical Systems and Signal Processing, vol. 15, no. 2, pp. 287-302.

[26] Mehala N., and Dahiya R., (2008): "A comparative study of FFT, STFT and wavelet techniques for induction machine fault diagnostic analysis," 7th WSEAS International Conference on Computational Intelligence, Man-Machine Systems And Cybernetics (CIMMACS '08), Cairo, Egypt, pp. 203-208, December.

[27] Devaney M.J., and Eren L., (2004): "Detecting motor bearing faults," *IEEE Instrumentation & Measurement Magazine*, vol. 7, no. 4, pp. 30-50.

[28] Tiwari R., (2010): "Analysis and identification in rotor-bearing systems," Developed under the Curriculum Development Scheme of Quality Improvement Programme at IIT Guwahati, Sponsored by All India Council of Technical Education.

[29] Trajin B., Regnier J., and Faucher J., (2010) "Comparison between vibration and stator current analysis for the detection of bearing faults in asynchronous drives," *IET Electric Power Applications*, vol. 4, no. 2, pp. 90-100.

[30] Bolaers F., Cousinard O., Marconnet P., and Rasolofondraibe L., (2004): "Advanced detection of rolling bearing spalling from de-noising vibratory signals," *Control Engineering Practice*, vol. 12, no. 2, pp. 181-190.

[31] Immovilli F., Bianchini C., Cocconcelli M., Bellini A., and Rubini R., (2013): "Bearing fault model for induction motor with externally induced vibration," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 8, pp. 3408-3418.

[32] Polikar R., (2007): "The engineer's ultimate guide to wavelet analysis- The wavelet tutorial," Rowan University, New Jersey, 2005.

[33] J. Zarei, and J. Poshtan, "Bearing fault detection using wavelet packet transform of induction motor stator current," *Tribology International*, vol. 40, no. 5, pp. 763-769.

[34] Eren L., and Devaney M.J., (2001): "Motor bearing damage detection via wavelet analysis of the starting current transient," Proceedings of the 18th IEEE Instrumentation and Measurement Technology Conference (IMTC 2001), Budapest, Hungary, pp. 1797-1800, May.

[35] Singh G.K., and S.A.S. Al Kazzaz, (2009): "Isolation and identification of dry bearing faults in induction machine using wavelet transform," *Tribology International*, vol. 42, no. 6, pp. 849-861.