Innovative Systems Design and Engineering
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online)
Vol 2, No 4, 2011
www.iiste.org

# Diagnosis of Broken Rotor Bar Fault of Induction Motor through Envelope Analysis of Motor Startup Current using Hilbert and Wavelet Transform

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## Abstract

This paper proposes a new method for extraction of low frequency oscillation from the envelope analysis of Motor Startup Current for diagnosis of Broken Rotor Bar Fault of Induction motor through Wavelet and Hilbert Transforms. The Envelope is the modulus of the Complex Analytic signal generated by using the original signal as the real part and its Hilbert Transform as the imaginary part. The concept of instantaneous frequency introduced in this paper is quite efficient to extract important transient fault informations, specially for non- stationary signal which is nonlinear. This method overcomes the difficulties of traditional FFT and Prony analysis as well as difficulties in selection of mother wavelet. Higher level detail coefficients correspond to narrow band low frequency components below the supply frequency are used to distinguish the faulty motor from the healthy one. Simultaneously this method has higher detectability and higher resolution and it can also deal with short data effectively, so it can be used online. This method has been validated in a laboratory standard.

**Keywords**: Envelope, Induction Motor, Broken Bar, Wavelet and Hilbert Transform, FFT, Prony, Instantaneous frequency, Reconstructed detailed Co-efficients

## 1. Introduction

Induction Motor is the principal drive in the industries because of its low cost, reliability, robustness, but in spite of these advantages, like other machineries, it undergoes fault specially when they are on sophisticated automatic online production process. If these faults are not detected at appropriate early stage, it may be severe, even may go to catastrophic, followed by unexpected breakdown, loss of downtime and ultimately, industry has to pay huge costs. Thus industry people feels that efficient on line condition based monitoring of faults at early childhood is desirable to detect and correct the faults to prevent the damage and to reduce the unwanted costs due to failure of Motor.

Commonly occurring faults in electrical drives and machines may be classified into**:**

Electrical Fault**:** stator winding short and open circuit, broken rotor bar and end ring fault

Mechanical Faults: rotor eccentricity, bearing damage, shaft misalignment and shaft bending.

From the study of the faults survey, reports in the review made by “Nandi et al. (2005)”, the percentage of rotor related faults is around 5-10% including broken rotor bar fault which is the subject of present discussion.

Broken Rotor Bar Fault:

This type fault is occurred in squirrel cage induction motor. During the course of running, during starting or load changing or voltage fluctuation or torque oscillation, large current may flow through the bars or end ring, large heat will be generated in the end ring joints or bars. This thermal stress cracks the end ring or the bar may also break. If the motor runs further, the large current will flow and excessive heat breaks the next bar as the previously broken bar being open, no current will flow through it and ultimate result will be complete shut down of the motor. This type of fault may not show any early symptoms, propagating to the next bars and leading to the sudden collapse unless continuous monitoring of fault have been carried out as reported in the paper by “Thomson, Fenger (2001)”.

Different fault diagnostic techniques have been proposed in the literature of which MCSA as revealed from the works, “Jung et al. (2006)”, “Blodt et al. (2006)”, “Mohanti and Kar (2006)” is the most spread non invasive method for monitoring of motor faults, specially broken rotor bar since decades. Other techniques such as speed and torque measurement by “Watson et al. (1994)”, vibration measurement by “Dorrel (1997)”, acoustic and noise monitoring by “Lee et al. (1994)”, and measurement of air gap flux by “Dorrel (1997)” need additional transducers and extra equipment to be fitted with the motor for measuring the signals which interrupt the operation as,“Watson and Paterson (1998)” confirmed in their works.The sensors and equipments required in these application are very costly. Their uses are only suggested for most expensive and load critical machines. Besides costs, extra problem arises as the sensor sensitivity changes due to environmental effect which makes the measurement unreliable. A cost effective alternative is current monitoring because of its easy availability, even some motors are provided with current measuring device for protection and control purposes. Out of these works using MCSA, most of the works are done on FFT analysis of motor stator current at steady state based on detection of the side band harmonics close to supply frequency , or its other harmonics illustrated in the papers, “Kia et al. (2007)”, “Cardoso et al. (1999)”, “Bellini et al. (2000)”, “Tallam et al. (2003)”, “Henao et al. (2004)”, expressed here as

$$f_{fault} = \left(1 \pm 2ks\right) f \tag{1}$$

where, f is the supply frequency and s is the slip, k =1, 2, 3, --------

This phenomenon is related to amplitude modulation (AM) of stator current induced by rotor structure modification due to broken rotor bar as claimed in the works, “Didier et al. (2006)”. In fact, the presence of stator current AM can not be detected without accurate time or frequency analysis. FFT method is used to transform discrete data from time domain to frequency domain for fault detection. But FFT method of analysis of the steady state current involves some important drawbacks when similar frequencies appear like those caused by broken bar due to load variation, machine inertia, torque and speed oscillation, supply voltage fluctuation observed in the review article, “Antonino et al”, the diagnosis will be confusing and wrong. Similar harmonics are also induced in the stator current depending on the motor constructional characteristics as seen in the review article, “Antonino et al. ”. It has been observed in the literature that the upperside bands are generally affected by the above factors for which researchers focussed their attention on lower side bands i.e. $f_{fault}$ = (1-2ks)f**.** Despite the use of left side band components below the supply frequency, the inherent power frequency spectral leakage as, “Didier et al. (2006)”, and “Douglas et al. (2005)”, have claimed, can completely hide or mask the lower side harmonic components specially for unloaded or lightly loaded motors, or when operating at very low speed because of sideband components’ low amplitude and their closeness to the supply frequency. Due to these difficulties, some authors developed new techniques based on the analysis of transient signals such as starting current, reported in the works of “Supangat et al. (2006)”, shut down voltage seen in the paper by “Lebaroud, Bentounsi (2005)” and startup vibration as reported in the research article by “Rodrugruez-Donate et al. (2008)” - an alternative source to detect fault.

In order to analyse transient signals , mainly during startup, several time frequency tools have been used such as STFT, Wavelet Transform both (CWT and DWT), WVD, Prony analysis and other tools. STFT with limited window size having often find it difficult to match with the frequency content of the signal which is generally not a known priori as described in the article by “Da-Silva et al. (1997)”. In applying Prony analysis, the effectiveness of fitting is sensitive to noise seen in the work done by “Marple (1987)”. In real problem, acquired signal data is always combined with noise. Though CWT has a very appealing feature of uniform resolution at each scale, but it has very poor resolution at its down side limited by the size of the wavelet function as claimed in the paper by “Yuping (2006)”. Besides, due to its continuous ranges of scales and shifts, its computational time become higher which is not desirable. The WVD is a time frequency representation method of a signal belongs to the Cohen class of distribution. The main disadvantage of this method is the appearance of several cross terms indicated by the existence of negative power for some frequency range as illustrated in the papers by “ Quian & Chen (1996)”. Apart from this, it also suffers from aliasing problem. To overcome the limitations described above of different signal processing techniques for motor fault analysis, some authors have applied DWT in their works as seen in the literature for detection of lower side harmonics (LSHs) from the transients, specially start up motor current by “Douglas et al. (2005)”, “Supangat et al. (2006)”, “Lebaroud & Bentounsi (2005)”, “Rodrigruez-Donate et al. (2008)”, “Antonino-Davieu et al. (2006a)”, “Zhang & Ren (2003)”. DWT is an efficient time scale method of analyzing a transient signal to achieve optimal frequency accuracy at low frequency bandwidth. The DWT technique uses variable size window and higher frequency resolution to match with the frequency content of the signal which is very important for transient analysis. Unlike other techniques, this method is focussed on high level wavelet signals (approximations and details). Co-efficients of detailed signals at higher level corresponds to low frequency bands or narrow band frequency components are used to distinguish faulty motor from the healthy one. It produces good results when no reliable results or informations obtained from FFT analysis as reported in the works, “Antonino-Davieu et al. (2006a)”. In spite of satisfactory performance of DWT applied for several kilowatts to several megawatt motor, it has some drawbacks. Selection of optimal mother wavelet is somewhat arbitrary, not a known priori which may introduce error in the detection parameters. Besides, the overlap between bands associated with wavelet signals appearing mainly for lower order wavelet (low number of filter coefficients)as seen in the article,“Antonino-Davieu et al. (2006b)” and the desired frequency response will be very poor. Some parts of fundamental frequency leaked into adjacent low frequency bands to mask these LSH completely. Further the edge distortion from the transform might in some cases make the detection of lower frequency band i.e below supply frequency difficult mainly if the startup transient is very fast as reported in his works, “Antonino-Davieu et al. (2006a)”. Again if we choice higher order wavelet to analyse using higher level coefficient, leakage due to overlap disappears. To overcome this constraint and limitations of FFT and other signal processing techniques including wavelets, a new innovative methodology have been proposed in this paper using envelope analysis of the signal through Hilbert Transform and DWT simultaneously. The concept of instantaneous frequency was used in the present analysis. The result is very excellent and promising for further research in area of the low frequency oscillation.

The paper is organized as section II presents theoretical background – the concept of Instantaneous frequency and Hilbert transform, Envelope detection and DWT. Proposed methodology and extraction of low frequency bands below supply frequency is also discussed. Section III discusses the experimental set up, in section IV results and data analysis were presented and possible advantages and disadvantages and in section V the conclusion for this paper were made.

## II. Theoretical background

Instantaneous frequency and Hilbert transform:

The concept of Instantaneous frequency is introduced for transient / non stationary signal analysis where the periodic frequency associated with some sinusoidal function looses its effectiveness. It is a time varying parameter which defines the spectral peaks varying with time. It has significant practical importance in radar, communication and biomedical application. It has only useful meaning for mono-component signal or narrow band of frequencies. Originally, it was defined in context of FM modulation theory. Instantaneous frequency is defined as $f_i = (1/2\Pi)\, d\Phi/dt$ i.e. phase variability. Shekel and Mandel challenged the physical interpretation of instantaneous frequency and argued that it is not unique function of time because any AM/FM wave to be represented in complex form as $m.e^{j\Phi t}$ seen in the research paper made by “Boashash (1992)”. To make an useful meaning of Instantaneous frequency, an unique complex representation of a signal say s(t) is obtained by using Hilbert transform whether or nor it corresponds to any physical reality and it can be treated like periodic sinusoidal frequency as Gabor and Ville noted as described above in the article,“Boashash (1992)”. The complex signal is known as analytic signal. If the real time signal is s(t) and its Hilbert transform H[s(t)], then unique complex representation of the signal according to Gabor and Ville may be written as

$$z(t) = s(t) + j[H[s(t)]] \tag{2}$$

The Hilbert transform is defined as

$$H\left[s(t)\right] = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(\tau)}{(t-\tau)}d\tau \tag{3}$$

Using the mean value theorem, we can evaluate

$$H\left[s(t)\right] = \frac{1}{\pi t}\otimes s(t) \tag{4}$$

Therefore, H[s(t)] is obtained from the convolution of the function 1/(Πt) with the original function s(t).

H[s(t)] and s(t) are supposed to be in quadrature because in theory they are out of phase by Π /2 i.e. Hilbert transform is equivalent to the positive frequencies from the spectrum of s(t) is shifted by - Π /2 and their amplitudes are doubled and the negative frequencies are removed. The Hilbert transform can be viewed as a filter which has the property to eliminate the negative frequencies and retain the positive frequencies with their phase shift of Π /2. The complex signal, z(t) is known as the analytic signal which does not always corresponds to the signal and its quadrature**.** When there may be significant leakages from positive spectral components into the negative spectral region, the HT will not produce quadrature component of input signal. Under such condition, analysis through this HT may leads to confusing results. If the signal is of the form, α(t)cosΦ(t) which is like a real FM signal and may be written as

$$z(t) = s(t) + jH\left[s(t)\right] = \alpha(t)\cos\Phi(\mathrm{t}) + \mathrm{jH}\left[\alpha(t)\cos\Phi(\mathrm{t})\right]$$

Or, $z(t) = \alpha(t)\left[\cos\Phi(\mathrm{t}) + j\sin\Phi(\mathrm{t})\right]$

or, $z(t) = \alpha(t)e^{j\Phi(\mathrm{t})}$ (5)

Now the analytic signal is of F.M. modulated form as given in (5). But If the spectra of α (t) and Φ(t) are not separately considered, the HT will produce overlapping and phase distorted functions.

For meaningful practical application, the amplitude spectra of α(t) and the phase spectra of Φ(t) are considered separately and the amplitude spectra of α(t) corresponds to low frequency zone of the system whereas the phase spectra of Φ(t) occupies high frequency portion. Our subject of discussion is only limited to low frequency amplitude spectra.

The analytic signal will be accurate complex representation of the real signal s(t) for narrow band amplitude spectra of α(t) only when the real signal, s(t) and its HT are in quadrature resulting better estimation of instantaneous frequency.

Envelope Detection:

The envelope of the signal, s(t ) is defined as modulus of analytic signal z(t), given by

$$E(t)=\left|s(t)+jH\left[s(t)\right]\right|$$

$$\text{Or, } E(t)=\alpha(t) \tag{6}$$

The analytic signal contains an amplitude component and phase component generally of which, our interest is focussed in low frequency zone of the analytic signal z(t **)** i.e. in the envelope α(t). It is a new dimension for detection of induction motor fault from the spectrum analysis of the envelope signal. The spectrum analysis of the envelope yields better detectability of fault than the spectrum analysis of the original signal as the power frequency is almost removed from the signal.

Wavelet Transform:

Wavelet is a time frequency tool which keeps intact the time frequency information during transient analysis. It decomposes a signal in both time and frequency in terms of a wavelet function called mother wavelet. The wavelet transform is governed by (7)

$$C(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t)\psi\left(\frac{(t-b)}{a}\right)dt \tag{7}$$

where x (t) is the signal, a and b being real denotes the wavelet scale and position, ψ is the wavelet function. A high scale wavelet corresponds to a low frequency stretched wavelet and low scale wavelet corresponds to high frequency compressed wavelet. There are two types of wavelet, the discrete wavelet transform (DWT) and continuous wavelet transform (CWT). DWT is preferred in the industry due its less computational complexity and less computational time compared to CWT as claimed in the works by "Lu and Paghda (2008)". In the present discussion, our attention is on DWT.

Discrete Wavelet Transform (DWT):

DWT decomposes a signal by passing it successively through high pass and low pass filters into its approximate and detailed versions using multi resolution analysis known as MRA as seen in the works by "Antonino-Davieu et al. (2006a)". Each step of decomposition of the signal corresponds to a certain resolution. Figure 1 shows two level wavelet decomposition. Here HPF and LPF are high pass and low pass filter respectively. At each level of scaling for various positions, the co-relation between signal and wavelet are called wavelet coefficients. High pass filter coefficients are called detailed coefficient ($d_n$) and low pass filter coefficients are called approximate coefficients ($a_n$). The first level of decomposition coefficients are $a_1$ and $d_1$, where $a_1$ is the approximate version of the original signal and $d_1$ is the detailed version of the original signal. At each decomposition level, the corresponding detailed and approximate coefficients have definite frequency bandwidths given by [0-fs/$2^{l+1}$] for approximate coefficient, $a_1$ and [fs/$2^{l+1}$ - fs/$2^{l}$] for detailed one $d_1$ where fs is the sampling frequency, l denotes the decomposition level limited by the sampling frequency fs ,where fs/2 is the corresponding Nyquist frequency. At each step of decomposition the sampled dataset are downsampling by a factor of 2↓, which is called dyadic decomposition.

From the first decomposition level, the detailed coefficient $d_1$ and the approximate coefficient $a_1$ are obtained. For further decomposition of $a_1$ gives $a_2$ and $d_2$ at level 2 and the process will be continued like this upto the maximum possible level. After decomposition of the signal, one can reconstruct and examine the constituent components of the original signal at each detail level (two level reconstruction through DWT shown in Figure2 ). The spectral frequency bands of different detailed coefficients are shown in the Table 1.

Proposed Methodology:

In the present paper, an innovative method has been proposed for the extraction of time varying low frequency oscillation from the induction motor startup current. The concept of instantaneous frequency has been introduced here to search for the spectral peaks which varies with time. It has only meaningful application for mono component or signals having narrow range of frequencies. The Hilbert transform is used here to generate complex analytic signal from an input signal, motor start up current which has single harmonic 50Hz surroundings. If s(t) is the signal and H[s(t)] its Hilbert transform, the analytic signal given in (2), z(t) accurately represents the original signal in its complex form only when s(t) and H[s(t)] are in quadrature, resulting better estimation of instantaneous frequency. But the components of z(t) are not always orthogonal because of leakage from positive frequencies to negative frequencies of the signal. The analysis using instantaneous frequency like the periodic frequency is possible when the analytic signal will be of the form of either FM or AM signal. As startup current is sinusoidal may be written as $\alpha$ (t)cos $\Phi(t)$, then the analytical signal, will be expressed in the form of $z(t) = \alpha(t)e^{j\Phi(t)}$ as given in (5) which is like FM signal. The analytical signal has two parts, amplitude and phase. $\alpha$ (t) is the modulus of the analytic signal given by $E(t)=| s(t) + jH[s(t)] |$ where E(t) being the envelope of the signal , the effect of supply frequency has been removed and this makes the analysis most effective. The amplitude spectrum belongs to the low frequency portion of the motor current signal which is addressed in this paper for detection of broken bar. For the meaningful application of instantaneous frequency, the processed signal i.e. the amplitude part of the analytic signal i.e. $\alpha(t)$ needs to be filtered in the narrow band zone. Higher order wavelet is the excellent choice to filter the narrow band frequencies below power supply frequency in its higher wavelet level detailed coefficients as shown from the Table-1. In the present work, higher level detailed coefficients using db10 at the levels 8th, 9th and 10th, the frequency bands are very narrow and below 50hz. At higher level of decomposition, overlapping of adjacent bands disappears, minimizing the possible leakage. The method of using Hilbert transform along with DWT presents an excellent method for detection of broken rotor bar fault using transient startup current, identifying the low frequency oscillation.

## III. Experimental set up

a) Block Diagram: The block diagram is shown in Figure 3. 3ph, 110V, 50Hz, supply is provided to the two induction motors of same rating one healthy, the other one with three number of broken rotor-bars, last one being intentionally made, faulty motor. The motors are run by direct-on-line supply.

b) Experimental Setup: Experiment was carried out on test-rig built by Spectra Quest, USA, having a high speed data acquisition system (OROS OR35, 8 channels, 100 mbps). Rating of the induction motors are 3ph, 1/3HP, 190V, 50Hz, 2980rpm. For capturing current signature Hall Probe (LEM PR30 ACV 600V CATIII 30Ampac/3Vac) is used. The experimental set up is shown in Figure 4. Transient current envelope has been captured with a sampling frequency of 8.192 kc / sec.

## IV. Results and discussions

The proposed method has been applied in the laboratory prototype for detection of induction motor broken bar fault (three bars broken). Two identical 3 ph induction motors, one healthy and the other with three broken bars of rating 1/3 H.P., 190 V, 50 hz, 2980 rpm were used. The starting current signatures for both the motors were captured using Hall probe sensors (LEM PR30 ACV 600V CATIII 30ampac / 3Vac) at a sampling frequency of 8.192 kc/s. The block diagram and experimental setup are given in Figure 3 and Figure 4. The captured motor current signatures for both the motors at no load and at single mass load and their signal envelopes (shown in Figures 5 ,6,7,8) are decomposed into details and approximate coefficients through DWT using " db10 "of Daubechies family upto wavelet level 10. The signal envelopes are the absolute value i.e the argument of the analytical signal obtained from the HT of the original signal. Each detail is then reconstructed.

Absolute reconstructed details of the starting current signals and their envelopes both for the faulty and healthy motor at load and at single mass load are shown in Figures 9-16 .

The whole analysis is performed using Matlab. Our objective is to extract lower side harmonics below 50 Hz for which higher order wavelet "db10" at higher levels 8th, 9th and 10th are utilized. Then the statistical parameters - the mean and the standard deviation of the absolute reconstructed detailed coefficients of the starting current signals and their respective signal envelopes for both the motors at no load and single mass load are estimated and considered as fault parameters . From the tables 2 and 3, it is observed that these values at 7th level for the original signal are much higher than the corresponding values for the signal envelope which ensures that the power frequency is not present in the signal envelopes which makes the detection easier and cleaner as the lower side harmonics are free from the spectral leakage effect of 50 hz . The DWT of the original signals are based on Fourier sinusoidal frequency whereas DWT of the signal envelopes works on the concept of instantaneous oscillating frequency. In comparison to the original signal, the envelope analysis provides better detectibility as it is observed from the curves in Figures 17,18,19,20 and Tables 2 & 3 that the curves representing the statistical parameters - mean and standard deviation of the absolute reconstructed detailed coefficients of the original signal lies below the curves representing those parameters corresponding to signal envelopes except at 8th wavelet level , the only mean corresponding to the original signal for the faulty motor at single mass load being higher value than the mean corresponding to the signal envelope of the healthy motor but still its value is less than the mean corresponding to the signal envelope of the faulty motor, this confirms that the fault parameters corresponding to instantaneous oscillating frequency of the signal envelopes have higher magnitude than those of the original signal, resulting higher detectibility and better representation of the non stationary starting current of the motors both at no load and single mass load. The signal envelope at no load produces higher values of the statistical mean and standard deviation of the absolute reconstructed details for faulty motor at 8th, 9th and 10th wavelet level than those of the healthy motor. The 9th level indicates much larger change of the respective parameter for the faulty motor than those for the healthy motor at no load. The signal envelope at single mass load gives higher values of statistical parameters - mean and standard deviation of absolute reconstructed details for faulty motor at 8th and 9th level, but less value at the 10th level than those for the healthy motor. Therefore, it is observed that the 9th level is most sensitive to detect fault (broken bar) both at single mass load and no load. Thus the lower side harmonics below 50 Hz is most effectively extracted from the signal envelopes.

It can be inferred from the observations discussed above that the envelope analysis based on instantaneous frequency gives better description of transient starting current of motor through Hilbert transform and Wavelet transform for detection of present broken bar fault.

Advantages and disadvantages : The main advantage of this method is that envelope detection using Hilbert transform based instantaneous frequency for extraction of lower side harmonics below supply frequency makes diagnosis easier and cleaner as because the power frequency is eliminated and the spectral leakage is minimized which improves detectibility. The method works with higher resolution due to choice of higher order wavelet at higher wavelet level to extract left side harmonics. The main disadvantage is once the sampling frequency is selected, the bands become fixed which means some ranges of frequencies are unexplored. In the present analysis, the range – ( 32 hz - 50 hz) is uncovered .

## V. Conclusion:

The main contribution in this paper is the application of new concept, instantaneous frequency through envelope analysis to extract low frequency oscillation. This is done by the use of Hilbert and Wavelet Transform. This method of diagnosis works with higher detectivity and higher resolution. Apart from this, it can also handle short data effectively. The no of computation is also less and simple compared to FFT and other time frequency techniques which makes the method suitable for online industrial application. The method may be extended to diagnose other faults of stator and rotor asymmetry including research in the areas of low frequency oscillations

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**Notes**

Note 1.From Figures 9 -20 absolute values of Reconstructed Details are plotted.

Table 1 Spectral Frequency Bands at different decomposition levels

| Decomposition Details | Frequency Bands(Hz) |
|---|---|
| Detail Level 1 | 2048 - 4096 |
| Detail Level 2 | 1024-2048 |
| Detail Level 3 | 512 - 1024 |
| Detail Level 4 | 256 - 512 |
| Detail Level 5 | 128 - 256 |
| Detail Level 6 | 64 – 128 |
| Detail Level 7 | 32 – 64 |
| Detail Level 8 | 16 – 32 |

| | |
|---|---|
| Detail Level 9 | 8 – 16 |
| Detail Level 10 | 4 - 8 |

Table 2. Statistical parameters of Absolute Reconstructed Details of Motor Current Signal

| Load | Motor Condition | Mean of absolute signal at Wavelet Level | | | | Standard Deviation of absolute signal at Wavelet Level | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 7 | 8 | 9 | 10 | 7 | 8 | 9 | 10 |
| No Load | Healthy | 2.973 | 0.2106 | 0.07209 | 0.03979 | 3.686 | 0.5152 | 0.07774 | 0.03629 |
| | Faulty | 2.821 | 0.2577 | 0.1469 | 0.1272 | 3.632 | 0.3432 | 0.1746 | 0.07431 |
| Single Mass Load | Healthy | 5.485 | 0.03797 | 0.03507 | 0.01162 | 4. 302 | 0.1446 | 0. 05344 | 0. 02548 |
| | Faulty | 5.3 | 0.0846 | 0.03208 | 0.01276 | 4. 249 | 0.1484 | 0. 04345 | 0. 02636 |

Table 3. Statistical parameters of Absolute Reconstructed Details of Motor Current Signal Envelope

| Load | Motor Condition | Mean of absolute signal Envelope at Wavelet Level | | | | Standard Deviation of absolute signal Envelope at Wavelet Level | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 7 | 8 | 9 | 10 | 7 | 8 | 9 | 10 |
| No Load | Healthy | 0.07287 | 0.271 | 0.4057 | 1.14 | 0.1616 | 0. 5472 | 0.5051 | 1.158 |
| | Faulty | 0.1982 | 0.2883 | 0.5345 | 1.226 | 0.3199 | 0.6174 | 0.8693 | 1.186 |
| Single Mass Load | Healthy | 0.03936 | 0.06242 | 0.0603 | 0.2097 | 0.08933 | 0.2903 | 0.2361 | 0.6743 |
| | Faulty | 0.06831 | 0.1219 | 0.09776 | 0.2019 | 0.1075 | 0.3018 | 0.2495 | 0.6459 |

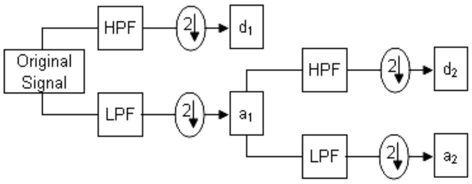

Figure 1 Two Level multiresolution DWT decomposition

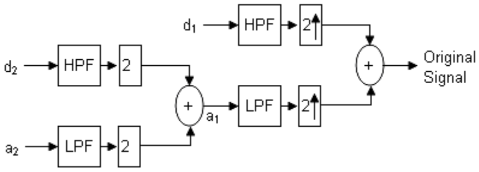

Figure 2 Two Level multiresolution DWT reconstruction

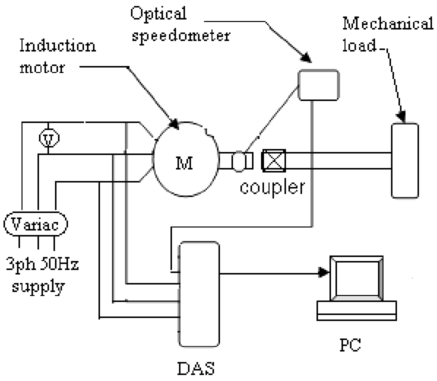

Figure 3 Block diagram of the experiment

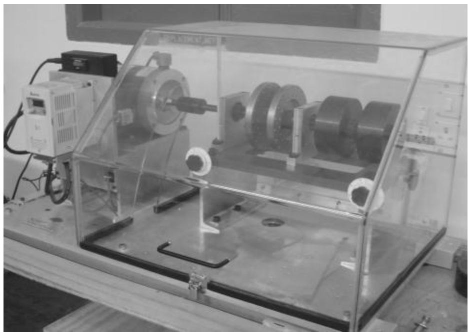

Figure 4 Experimental Setup

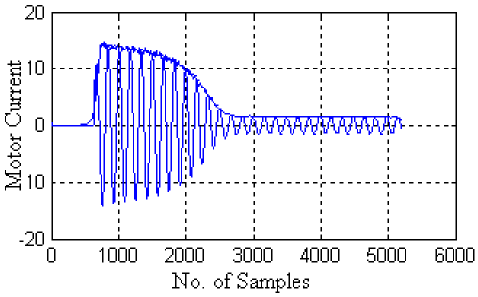

Figure 5 Healthy signal and its envelope at no load

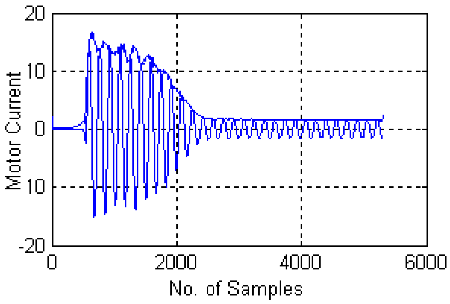

Figure 6 Faulty signal and its envelope at no load

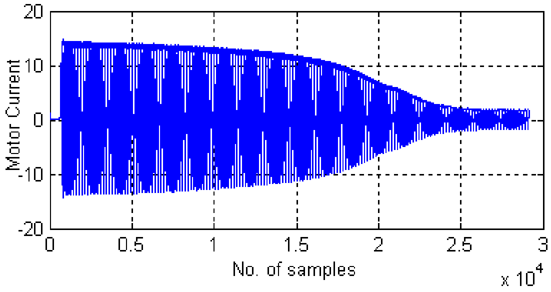

Figure 7 Healthy Signal and its envelope
at single mass load

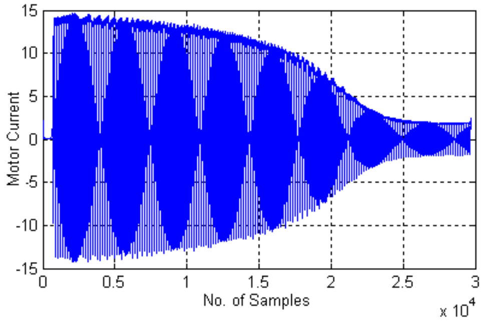

Figure 8 Faulty Signal and its envelope
at single mass load

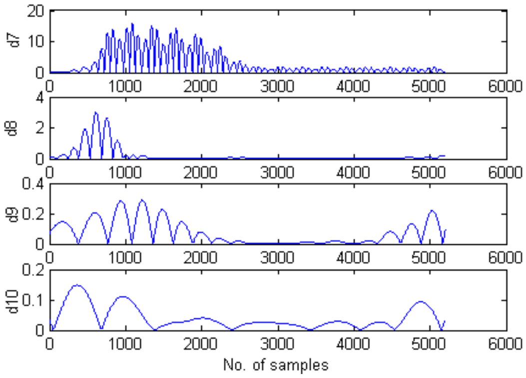

Figure 9 Reconstructed Details of motor
(Healthy) current signal at no load

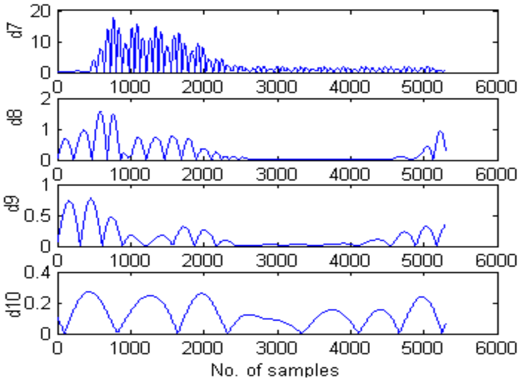

Figure 10 Reconstructed Details of motor
(Faulty) current signal at no load

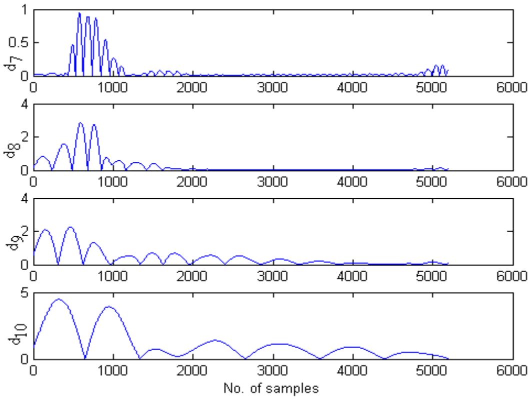

Figure 11 Reconstructed details of motor
(Healthy) current signal envelope
at no load

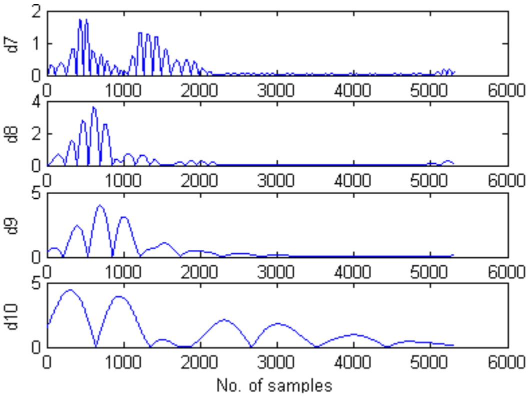

Figure 12 Reconstructed details of motor
(Faulty) current signal envelope
at no load

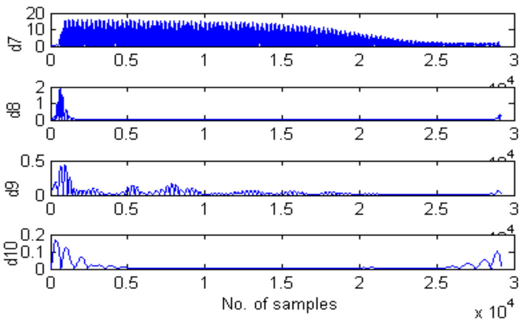

Figure 13 Reconstructed details of motor (Healthy) current signal at single mass load

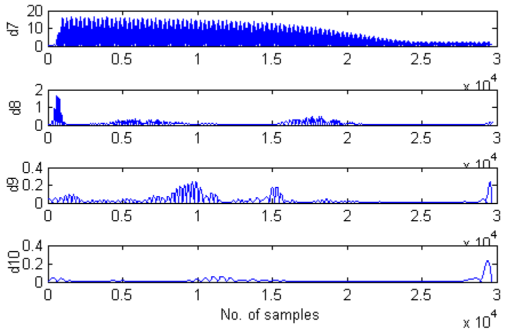

Figure 14 Reconstructed details of motor (Faulty) current signal at single mass load

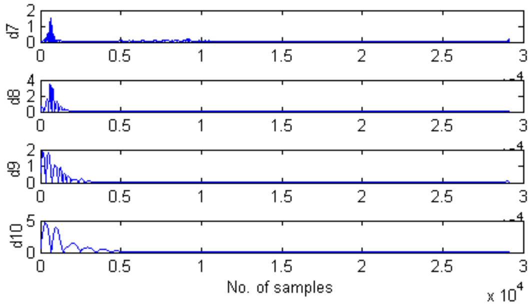

Figure 15 Reconstructed details of motor (Healthy) current signal envelope at single mass load

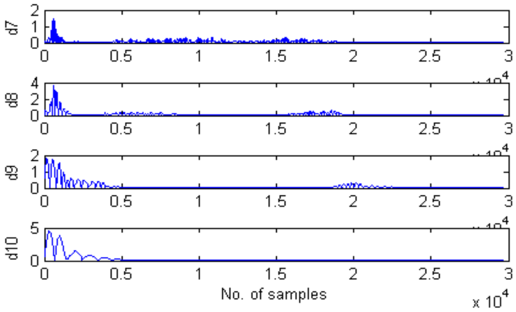

Figure 16 Reconstructed details of motor (Faulty) current signal envelope at single mass load

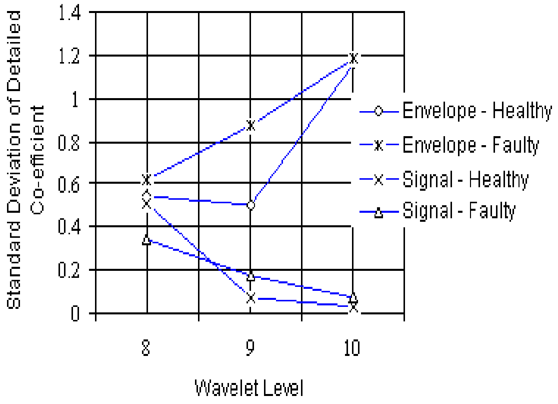

Figure 17 Mean of Reconstructed Details of Stator Current at No Load

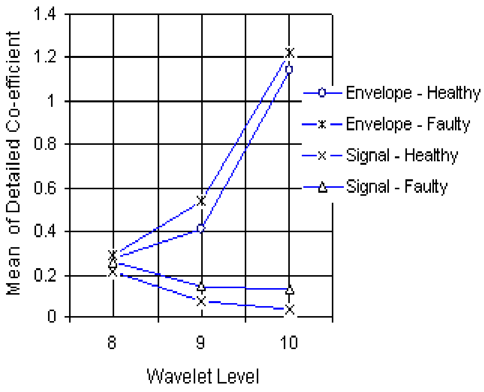

Figure 18 Standard Deviation of Reconstructed Details of Stator

Current at No Load

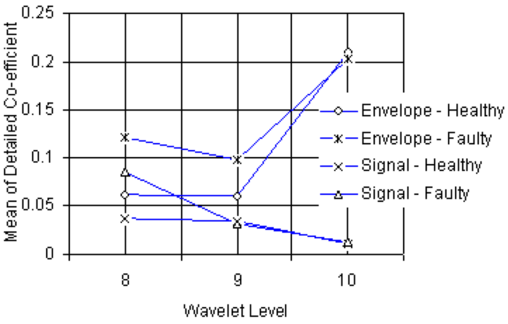

Figure 19 Mean of Reconstructed Details of Stator Current at Single Mass Load

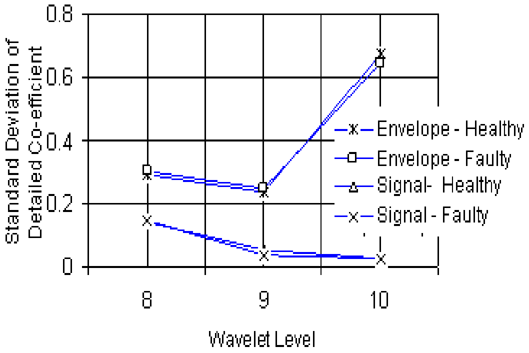

Figure 20 Standard Deviation of Reconstructed Details of Stator Current at Single Mass Load

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