

Incipient Fault Detection of the Inverter Fed Induction Motor Drive

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ABSTRACT

Inverter fed Induction motor drives are deployed across a variety of industrial and commercial applications. Although the drives in the question are well known for their reliable operation in any type of environment, it becomes an important daunting critical task to have them in continuous operation as per the applications' requirement. Identifying the faulty behavior of power electronic circuits which could lead to catastrophic failures is an attractive proposition. The cost associated with building systems devoted for monitoring and diagnosis is high, however such cost could be justified for the safety-critical systems. Commonly practiced methods for improving the reliability of the power electronic systems are: designing the power circuit conservatively or having parallel redundant operation of components or circuits and clearly these two methods are expensive. An alternative to redundancy is fault tolerant control, which involves drive control algorithm, that in the event of fault occurrence, allows the drive to run in a degraded mode. Such algorithms involve on-line processing of the signals and this requires Digital Signal Processing of the signals. This paper presents the FFT and Wavelet transform techniques for on-line monitoring and analyzing the signals such as stator currents.

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1. INTRODUCTION

Variable Frequency drives (VFD) are being used in greater numbers throughout a wide variety of industrial and commercial applications due to their numerous advantages, so, appropriate diagnostic means must also be used to monitor the status of the drive or components of drive to make sure the safety of the controlled system [1]. Sophisticated automation industry or process requires Inverter fed induction motor drive system (Figure 1), which demands cautious coordination of variable frequency Inverter with the Induction motor. Also, it must be able to provide payback period along with serving actual needs of design process. The importance of incipient fault detection is the cost-effectiveness that is accomplished by diagnosing potential failures ahead they occur [2].

Incipient fault detection, allows preventative maintenance to be scheduled for machines that might not ordinarily be due for service and may also prevent an extended period of downtime caused by extensive motor failure. In the present-day industries, consistent functioning of numerous electric drives is essential for overall plant operation, and failures of such drives or portion of drives must be protected ahead of fault occurrence. If such developing fault, for example, an interturn short circuit, or low-voltage ride through fault, is detected, it is feasible to provide planned shutdown or change the configuration of drive to run at degraded status of operation [3]. Supervising consistently in such cases will be cost effective, and it enables the machine to be replaced or reduce the repair time, if the fault has been detected at the earliest.

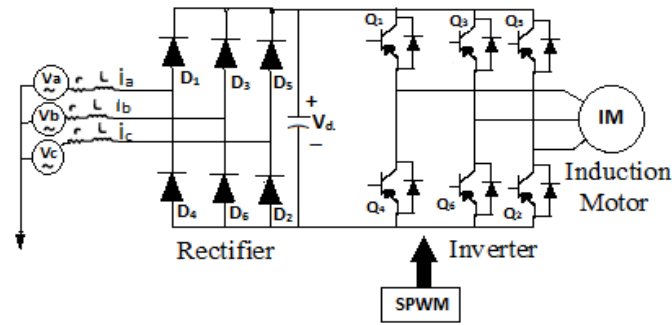


Figure 1. Variable Frequency Drive (VFD)

For accurate and right timings of fault detection, the advanced signal processing techniques such as Fast Fourier Transform (FFT), Wavelets to be employed. The advent and application of Genetic algorithms, Artificial Intelligence have been helpful in bringing in the ‘human like’ thinking and far superior control systems. Application of such significant advancements to condition monitoring and fault diagnostics of the drive system has been very helpful in precisely identifying and locating incipient faults [4].

Induction motors employed in ac motor drive systems are normally fed by voltage-source inverters (VSI), such drives are sensitive to different kinds of faults, in case of such fault occurrence, the drive function must be stopped for a no preprogrammed maintenance schedule, which costs very high. So, this warrants to develop incipient fault detecting tools and techniques [5].

In variable frequency Induction motor drive, if any of the input supply lines disconnected due to fault in supply lines or malfunction of any device in converters which are used to conjoin the supply and Induction motor, causes drive to run in single phase operation called fault tolerant mode. Such condition allows to develop the undesirable torque pulsations which must be nullified and load torque must be reduced to protect the drive from further deterioration. [6]. The block diagram of Figure 1 has been used for simulation studies.

2. FAST FOURIER TRANSFORM (FFT)

Innovative technique in finding fault play vital role and demand for such technique is increasing drastically, which also, enhances the dependability on such technique. The Fast Fourier Transform is(FFT), to some extent, helps in finding the fault in predictive manner which may help preplanned or pre-programmed schedule in protecting the drive from catastrophic faults. To recognize various motor faults, FFT algorithm can be employed, and the following equations can be employed to compute the amplitude and phase versus frequency from the FFT [7].

$$\text{Amplitude spectrum in quantity peak} = \frac{\text{Magnitude[FFT(A)]}}{N} = \frac{\sqrt{\text{real[FFT(A)]}^2 + \text{imag[FFT(A)]}^2}}{N} \quad (1)$$

$$\text{Phase spectrum in Radians} = \text{Phase [FFT(A)]} = \arctangent\left(\frac{\text{imag[FFT(A)]}}{\text{real[FFT(A)]}}\right) \quad (2)$$

Where the arctangent function here returns values of phase between $-\pi$ and $+\pi$, a full range of 2π radians.

Using the rectangular to polar conversion function to convert the complex array $\frac{\text{FFT(A)}}{N}$ to its magnitude and phase (Φ) is equivalent to using the preceding formulae.

To view the amplitude spectrum in rms volts (or another quantity), divide the non-DC components by the square root of 2 after converting the spectrum to the single-sided form. Because the non-DC components were multiplied by two to convert from two-sided to single-sided form, the rms amplitude spectrum can be calculated directly from the two-sided amplitude spectrum by multiplying the non-DC components by the square root of two and discarding the second half of the array. The following equations show the entire computation from a two-sided FFT to a single sided amplitude spectrum.

$$\begin{aligned} \text{Amplitude spectrum in rms} &= \sqrt{2} \frac{\text{Magnitdute}[FFT(A)]}{N} \text{ for } i = 1 \text{ to } \frac{N}{2} - 1 \\ &= \frac{\text{Magnitdute}[FFT(A)]}{N} \text{ for } i = \end{aligned} \quad (4)$$

Where 'i' is the frequency line number (array index) of FFT of A. To view phase spectrum in degrees, the following Equation can be used:

$$\text{phase spectrum in degrees} = \frac{180}{\pi} \text{Phase FFT}(A) \quad (5)$$

The amplitude spectrum is closely related to the power spectrum. Single sided power spectrum can be computed by squaring single-sided rms amplitude spectrum. Conversely, the amplitude can be computed by taking square root of the power spectrum [8].

3. WAVELET TRANSFORM (WT)

Fourier transform decomposes a signal into a family of complex sinusoids, whereas the wavelet transform decomposes a signal into a family of wavelets, which are different from sinusoids, i.e. they may be symmetric or asymmetric, proper or improper shape and continuous. The wavelets clan consists of the augmented and translated versions of a prototype function, this prototype function is called a mother wavelet. The scale and shift of wavelets determine how the mother wavelet augments and translates along the time or space axis. The trusted results can be obtained by using wavelets since the wavelets patterns can be selected based on feature of fault signals [9]-[10]. Because of localization of wavelets in both time and frequency, they have limited time duration and frequency bandwidth and its localization property can be used to represent a signal with a few coefficients.

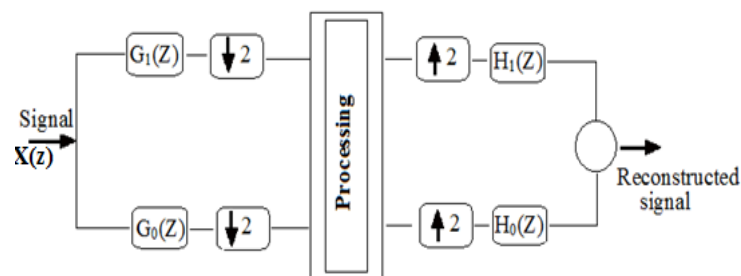


Figure 2. Perfect Reconstruction (PR) filter bank system

Figure 2 shows a typical two-channel Perfect Reconstruction (PR) filter bank system. At first the signal $X(z)$ is filtered by a filter bank which contains $G_0(z)$ and $G_1(z)$. The outputs of $G_0(z)$ and $G_1(z)$ then are down sampled by a factor of 2. On processing, the modified signals are up sampled by a factor of 2 and filtered by another filter bank consisting of $H_0(z)$ and $H_1(z)$. In case of no process done between two filter banks, total output value of $H_0(z)$ and $H_1(z)$ is like the initial signal $X(z)$, except for the time delay.

In this two-channel PR filter bank, $G_0(z)$ and $G_1(z)$ forms analysis filter bank, and $H_0(z)$ and $H_1(z)$ forms synthesis filter bank. $G_0(z)$ and $H_0(z)$ are usually low pass filters, and $G_1(z)$ and $H_1(z)$ are normally high pass filters. The low pass filters and high pass filters are indicated by subscript 0 and 1 respectively. The operation 2 denotes a decimation of the signal by a factor of two and using decimation factors to the signal confirms that the number of output samples of the two low pass filters equal the number of initial input samples $X(z)$. Therefore, no superfluous information is added during the decomposition. Two-channel PR filter bank system can be used and consecutively decompose the outputs of low pass filters, as shown in Figure 2.

High-frequency fluctuations from the signal are eliminated by low pass filters and preserve slow trends, and these outputs of low pass filters provide an approximation of the signal. on the other hand, the high pass filters discard the slow trends from the signal and preserve high-frequency fluctuations and these outputs of high pass filters provide elaborate signal information. The outputs of low pass filters and high

pass filters define the approximation coefficients and elaborate coefficients, respectively. Symbols A and D in Figure 3 represent the approximation and elaborate information, respectively.

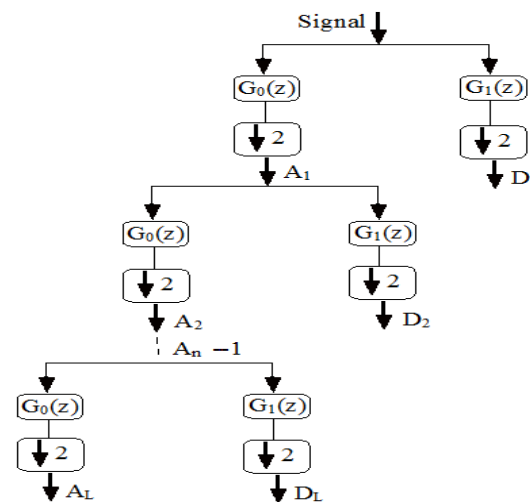


Figure 3. Discrete Wavelet Transformation

Elaborate coefficients can be called wavelet coefficients because elaborate coefficients approximate the inner products of the signal and wavelets. The Wavelet Analysis Tools use the subscripts 0 and 1 to describe the decomposition path, where 0 indicates low pass filtering and 1 indicates high pass filtering. For example, D_2 in Figure 3 denotes the output of two cascaded filtering operations—low pass filtering followed by high pass filtering. Therefore, this decomposition path can be described with the sequence 01. Similarly, D_L represents the output of the filtering operations 000...1 in which the total number of 0 is $L-1$. The impulse response of 000...1 converges asymptotically to the mother wavelet and the impulse response of 000...0 converges to the scaling function in the wavelet transform [9,7,11]

4. FAILURE MECHANISM IN INVERTER

The semiconductor devices which are employed in power inverter circuits need to withstand in an environment involving hasty speed variation, frequent stopping and starting and frequent overloading. Even though, the auxiliary snubber circuits help in suppressing the sudden over-current and over-voltage, however, the inherent incipient faults due to diode shorting, etc. cannot be neglected and must be monitored to avoid fault escalation into the deeper circuits, which helps in protecting the drive from larger damages and in turn financial losses. [12]-[13].

Electrical over Stress (EOS) is a failure mechanism which occurs when the device is driven off from the Safe Operating Area (SOA) and this is normally due to overstresses caused by sudden changes in the device parameters resulting into catastrophic fault. The other class of failures is associated with the intrinsic aspect of a component and be a fatigue effect. For example, it is known that, the internal structure of the device could be permanently altered due to the current flowing though it culminating in occurrence of failure even when the device is working within SOA [1].

EOS, is a phenomenon where electrical signals applied to a circuit or a device exceed normal operating values. Research literature published by Intel indicates that EOS is the number one cause for damaging the IC components. EOS usually leads to catastrophic faults involving the standard system protection and no matter what is deployed for preventive diagnostics. A typical example of EOS induced failure in power converters application is high-voltage breakdown: this failure should obviously be avoided by means of over-voltage protection. Power-frequent under-voltages may also lead to tripping of the converter if not the condenser capacity is high enough. Some types of faults, that not always lead to a failure, for instance that the motor is not running smoothly, are typical for legacy VFDs. Such faults can be traced back to the DC-bus capacitors, or to aging of the components in the control circuits [1],[14].

5. SIMULATION RESULTS AND DISCUSSION

The faulty conditions were studied by simulation and the data analysis has been performed on selected faults using FFT.

Table 1. The Inverter fed Induction Machine ratings used for Simulation studies.

Sl. no.	Particulars	Ratings
1	Machine name plate rating	415V, 3hp, 50Hz, 1440RPM
2	Stator resistance per phase(R_s)	0.0453 P U
3	Stator leakage reactance per phase(X_{ls})	0.0775 P U
4	Mutual reactance per phase(X_m)	2.0420 P U
5	Rotor Resistance per phase(R_r)	0.0222 P U
6	Rotor Leakage Reactance per phase(R_r)	0.03222 P U
7	Machine inertia(H)	1.0 P U

5.1. Fast Fourier Transform (FFT)

Under continuously varying load conditions accurate fault detection in the drive or parts of drive is most important. The FFT is useful in finding failures in the static signals due to its functioning in the frequency domain only. Also, the FFT-based Motor Current Signature Analysis relies on sideband components around elemental harmonic fault detection where the amplitude of side-band components varies along with load, and therefore, it is more apt to detect fault under balanced load but not in varying loads [15].

Observing slight changes in the magnitude of healthy FFT signal in the Figure 4(a) and signals under fault condition in Figure 4(b), Figure 5(a) and Figure 5(b) with different fault occurring periods. Also, these Figures display the sum of frequency component under faulty conditions but indicates no fault occurrence time.

To understand the above FFT signal with different fault variation in time shows that, as per Heisenberg Uncertainty principle, "bandwidth" (frequency spread) and "duration" (temporal spread) cannot be modified arbitrarily small [16]. The classical Fourier transform of a function allows you to make a measurement with zero bandwidth: the evaluation $f^{\wedge}(k)$ tells us precisely the size of the component of frequency k . But by doing so you lose all control on spatial duration: you do not know when in time the signal is sounded. i.e. absolute precision on frequency and zero control on temporal spread. Due to this reason the FFT signal will not clearly mention fault occurrence timing in the dynamic systems. So, the processor may not be able to decide to reschedule the drive to degraded mode of operation if possible, or may not be able to break the circuit at earlier stage of faulty signal to avoid escalation of fault into other parts of the drive [12],[16].

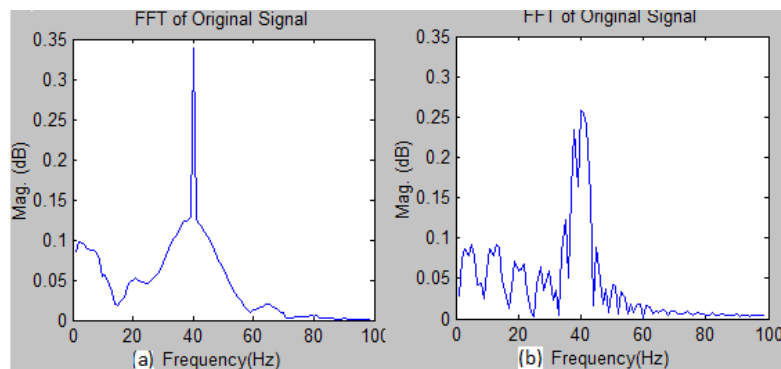


Figure 4. (a)FFT signal for healthy drive, (b) FFT signal for 0.1 sec faulty open period(0.4-0.5)

Figure 4 to Figure 5, the FFT signals are displayed for healthy drive to faulty drive signals. The faulty signals are in descending order of fault periods, i.e. the fault period of 0.1 sec, 0.01 sec, and 0.001 sec respectively. These filtered power spectrum signals show slight changes from healthy signals in magnitude of frequency domain but no fault occurrence time. If the fault has been identified at earlier stage with clear fault initiation time, the chance of rescheduling the drive with modified circuit to run in degraded mode if drive configuration permits or to break the circuit to protect the drive from fatal damage is possible. As the fault timing is not precise, so the immediate action to protect the drive gets delayed.

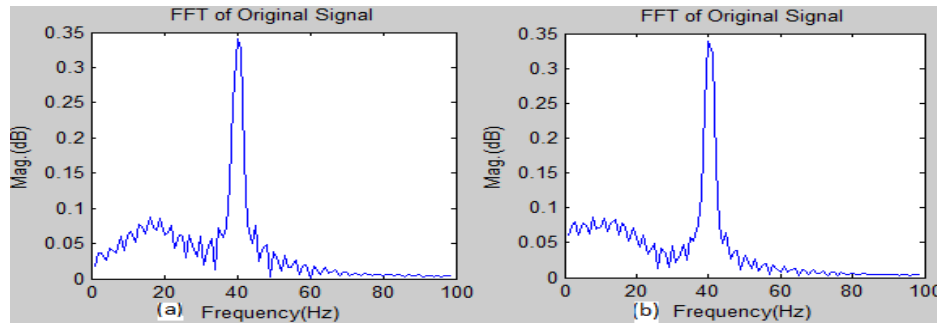


Figure 5. (a) FFT signal for 0.01 sec faulty open period(0.5-0.51) (b) FFT signal for 0.001 sec faulty open period (0.5-0.501)

5.2. Wavelet Transform (WT)

For nonperiodic, nonstationary, short duration and impulse super-imposed nature signals the wavelet transform is one of the most suitable tool for the analysis. So, the wavelet transform (WT) is a powerful tool for the analysis of current transient phenomena, due to its ability to extract information from transient signals simultaneously in the time and frequency domain. In this paper, the application of wavelet transforms to determine the accurate classification for the change in the wave shape due to fault occurrence is investigated.

Early diagnosis can help to avoid unplanned standstill, to make possible to run an emergency operation in case of a fault or to keep the time to repair short in case of a fault. The WT signal aids in decision taking for immediate action to be implemented [17]. Standard deviation of 1.589 has been observed for WT signals.

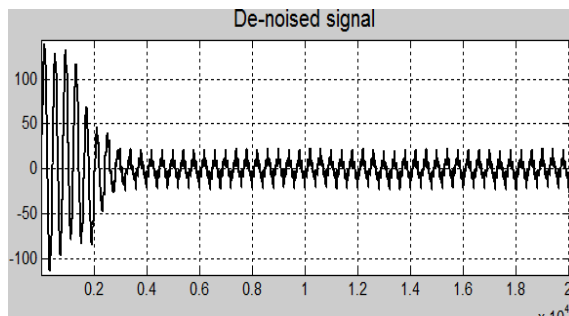


Figure 7. Denoised signal from debauches under healthy condition

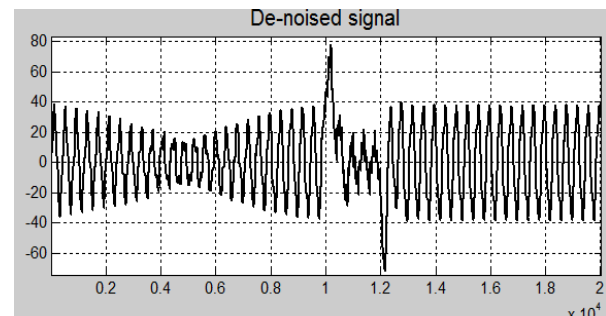


Figure 8. Denoised Signals for faulty Phase 'a' open for 0.1 sec period

An advantage of wavelet transform during signal decomposition is that it allows the user to analyze the information contained in a non-stationary signal at different time–frequency resolutions. The WT method can be considered as a complementation of traditional FFT method to non-stationary states. This detection procedure can be chosen as indicative of new shift, where FFT does not fit into [16].

Observing the Wavelet signals from Figure 7 to Figure 11, it is very clear that signal extraction indicates the time of fault along with magnitude when compared to FFT signals, which enables assertion on fault location and time in the drive. This would aid the software program to decide between continuing the operation under partial load condition or to shut down the machine.

Signals do not exist without noise, it must be removed from the data for further data analysis. Wavelet Transform (WT) is a powerful tool for removal of noise from faulty signals due to its perfect reconstruction filters, which is very clear from the de-noised from Figure 7 through Figure 11 [18]-[19].

The wavelet transform take advantage of the intermediate cases of the Uncertainty Principle. Each wavelet measurement, i.e. the wavelet transform corresponding to a fixed parameter informs on the temporal extent of the signal, as well as on the frequency spectrum of the signal. i.e. from the parameter w (which is the analogue of the frequency parameter k for the Fourier transform), characteristic frequency $k(w)$ and a characteristic time $t(w)$ can be derived, and initial function includes a signal of “frequency $k(w)$ ” that happened at “time $t(w)$ ” [20].

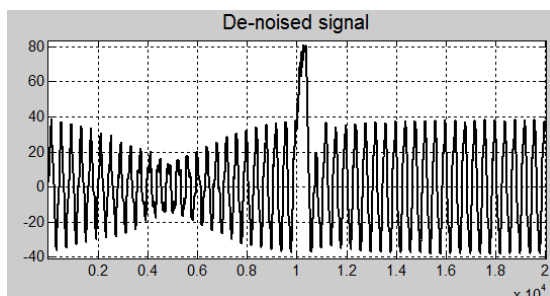


Figure 10. Denoised Signal for faulty phase 'a' open for 0.01 sec

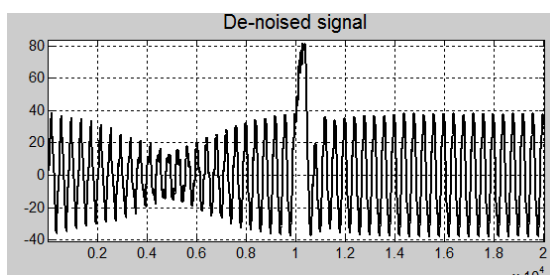


Figure 11. Denoised Signal for faulty phase 'a' open for 0.001 sec.

The magnitude and the fault occurrence time has been displayed even at lowest fault period of 0.001 sec in Figure 11, which enables protecting the drive at earlier stage, i.e. incipient fault diagnosing may be possible by using WT signal. The fault period up to 0.001 sec has been considered, since less than 0.001 sec period is not feasible for the drive to respond due to limitation of Pick up time of sensors and relays [21]. In the paper published in IEEE proceedings have compared about the differences on FFT and WTs diagnosis with general fault finding [22]. This paper describes the sensitive differences of FFT and WTs in detecting incipient faults. Next research paper discussion will be on choosing specific wavelet classification to find incipient fault, i.e. for example choosing Db4 signal to identify the incipient fault.

6. CONCLUSION

It becomes more important to safeguard the drive from the inevitable fault conditions, so diagnosing the faults is critical. Overall from the standpoint of an advanced robust system design, better protection, and fault tolerant control system it is very important to understand the behaviour of incipient faults which will eventually lead to the more serious faults. The FFT and Wavelets based fault diagnosis approaches, simulation results and comparison of the simulation results are presented in this paper. These algorithms can be realized by writing a software program on a general-purpose Digital Signal Processor thereby reducing the cost significantly as compared to any other methods. To conclude, on-line monitoring of the drive system signals help in the detection of the incipient faults which can lead to scheduling preventive maintenance ahead of the occurrence of the actual faults, resulting in cost savings (as compared to the unscheduled shutting down of the system) and the most important benefit amongst the others is the drive control systems can accommodate the future enhancements by the means of software update.

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