Real Time Condition Monitoring of Induction Motor Using an Embedded System

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Abstract— **In spite of advanced control and monitoring systems the induction motor undergoes numerous faults and these faults result in lowering of overall industrial productivity and increased shutdown period. Thus, there is the need of prior detection of faults while in the motor operation. The prior detection of faults in induction motor and its optimal diagnosis can facilitate the industry to function with least unexpected maintenance and production shutdown. In order to build a system model for real time fault diagnosis and condition monitoring method a Field Programmable Gate Array based system with Digital Signal Processing techniques approach has been developed for identifying faults in induction motor. Implementation with FPGA opens a wide door for its employment in numerous industrial and real time applications development.**

Keywords— **Induction Motor, Embedded system, FPGA, Condition monitoring, Fault frequencies**

1 INTRODUCTION

Induction motors play a very significant role in the growth and overall productivity optimization for industrial drive applications. The majority of the condition monitoring approaches for induction motors generally deal with a specific fault detection. This paper proposes an investigation technique for the detection of two or more mixed faults of an induction motor. This is a new methodology that suits for hardware furtherance which interfaces induction motor with cRIO (compact Reconfigurable Input/Output) system to identify the faults viz broken rotor bars, eccentricities, bearing degradation and stator winding status. To ensure the performance response of the proposed methodology, tests are carried out on a 2 kW induction motor in a laboratory, which show satisfactory results that prove its suitability for on-line detection of single and multiple mixed faults in an adaptable way through its hardware implementation using FPGA interface.

In the last three decades, a large amount of research work has been published on using the stator current spectrum to sense the rotor faults linked with mechanical unbalance and broken bars of rotor [1]. These techniques demand highly skilled user in order to distinguish a normal operating condition from a possible failure state. This is so, as the monitored spectral components (either current or vibration), are based on a number of factors, including normal operating conditions [2,3].

Now a day, the employment of cRIO is an attractive method that exhibits flexibility and improved performance along with its compact size. This technique has been employed for various applications such as medical equipment monitoring [12], automatic control in automobiles [4], Missile Electro-hydraulic Servo Mechanism [15], etc. Hence, the research effort has been made in the effective utilization of LabVIEW, cRIO with the FPGA environment for the monitoring of induction motor. The uniqueness of this technique is that, it receives multiple sensor signals and is capable of analysing with custom signal analysis tools. Moreover, this system provides an on-line condition monitoring platform with custom-built indicator modules[16].

2 FAULT FREQUENCIES IN INDUCTION MOTORS

It is well known that, a current spectrum of a faulty system is composed of potential fault information. However, the frequency components of each fault can be determined through various techniques. It is also important to know that, just as in vibration analysis, as the fault progresses, its characteristic spectral components continue to increase over a time.

Bearing Faults:

The bearing fault current harmonics can be described [1, 3, 11], by following equations,

$$f_{bb} = f_s \pm n_b . f_{bb\,(o,i)} \qquad (1)$$

Where f_s is supply frequency of the system. f_{bbo} and f_{bbi} are related to outer and inner race, respectively, and n_b is the number of balls, and f_0 and fi are given by,

$$f_{bbo} = \frac{f_r}{2}\left[1-\frac{BD}{PD}\cos\beta\right] \text{ and } f_{bbi} = \frac{f_r}{2}\left[1-\frac{BD}{PD}\cos\beta\right] \qquad (2)$$

Where, 'BD' and 'PD' are, respectively, the ball diameter and the pitch diameter, β is the contact angle between the balls and the ball bearing rings and fr the rotor frequency.

$$f_{bb}=(f_s \pm m.f_v) \qquad (3)$$

Where, f_{bb} denotes bearing fault frequencies, m an integer and $f_{v,}$ the vibration frequencies.

Rotor faults:

End rings and broken bars of the rotor induce the same harmonics in the stator currents. Hence, the amplitude of stator current will be modulated by the slip frequency factor, which is given by 2.s.fs. Here '*s*' is per unit slip. This increase in the modulation is based on the severity of the fault. In the current spectrum, the harmonics [11-13] due to the rotor fault can be found from the following characteristic equation:

$$f_{br} = f_s.\left(1 \pm 2s\right) \quad (4)$$

Stator Faults:

The stator current related faults can be identified by using the fault frequency measurement, which can be observed by the FFT analysis of the voltage, current and axial flux signals [11-12, 14].

$$f_{st} = f_s\left[\frac{n(1-s)}{p} \pm k\right] \quad (5)$$

Where, '*p*' is the number of pole pairs of the induction motor and 'k' is an integer. It has been reported that, 2.fs or a combination of rotor frequency f_r, 2.f_r, and 2.f_s can be an indication of stator faults in vibration based monitoring.

Eccentricity Faults:

In the literature, other possible mechanical imbalance faults of induction motor have been reported in [1,3,11,12]. Eccentricity is also one of the major kinds of induction motor faults in which the frequency analysis is made based on following expression:

$$f_{ec} = f_s.\left[1 \pm \left(\frac{1-s}{p}\right) \pm n\right] \quad (6)$$

Where,

f_{ec} = eccentricity frequency, f_s = supply frequency, r = number of slots

p = pole pairs, n = 1, 3, 5…

3 REAL TIME SYSTEM FOR CONDITION MONITORING

This method of condition monitoring of induction motor is implemented with FPGA interface for obtaining on-line operation with early identification of faults. It is recommended that the cRIO is the most suitable system for real-time processing units [11], which can be easily reconfigured, and provides superior and parallel operation of tasks. The optimized program has been developed for condition monitoring of induction motor in the LabVIEW environment, which considerably accelerates the execution time and accommodates an open architecture for further improvements.

Figure 1 shows the block diagram of fault detection and condition monitoring system. In this system, signal outputs obtained from sensors are fed to the signal conditioning blocks. There are eight different signal channels, which are multiplexed through analog to digital converters for necessary processing and diagnosing. Figure 2 shows the experimental setup of cRIO based Induction Motor Diagnosis system.

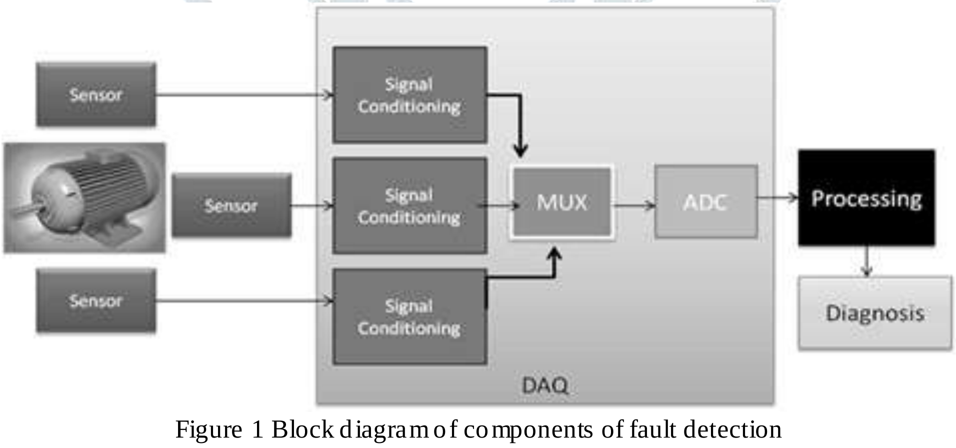


Figure 1 Block diagram of components of fault detection and condition monitoring system

Figure 2 Experimental setup of cRIO based Induction Motor Diagnosis

Figure 3 shows the block diagram of cRIO based real time condition monitoring system for induction motor. In this system, cRIO consists of RT controller 9004, Signal processing module and FPGA 9104 unit. Suitable sensors are used for data acquisition from the motor and for further diagnosis in cRIO system. The exceptional computational feature of the cRIO based system is that it includes both a real-time processor and an FPGA. Both modules are programmable using the LabVIEW graphical user interface. With this blended architecture, multiple diagnosis algorithms and approaches can be rapidly designed, developed and tested on the drive system.

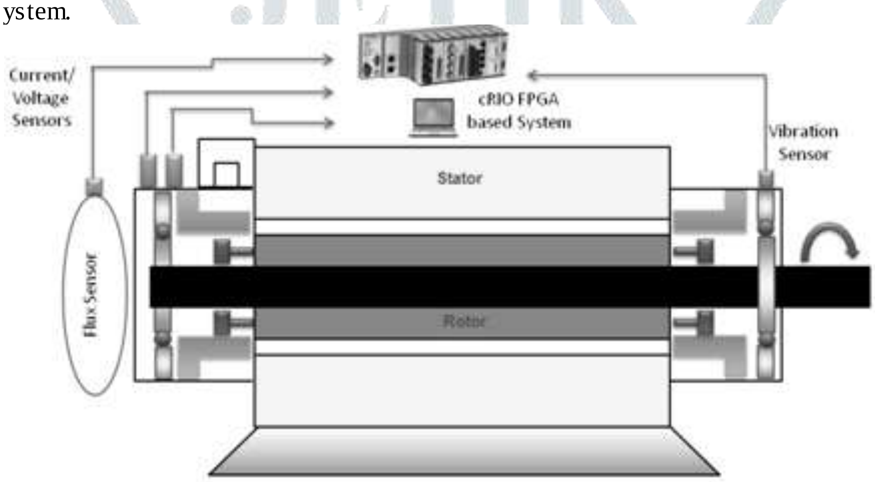


Figure 3 Block diagram of Induction Motor condition monitoring System with sensors

4 REAL-TIME SYSTEM DEVELOPMENT

This is the core of the system which significantly reduces the complexity, operational time and it also provides tools for monitoring and detection of faults in the system. cRIO technology blends the flexibility and the processing power of a field programmable gate array FPGA with greater reliability of a real-time processor. cRIO consists of three constituents: (i) processor to execute LabVIEW applications for the real-time operating system RTOS (ii) reconfigurable embedded chassis with FPGA core that can be accessed and configured using LabVIEW graphical development environment and (iii) industrial grade Inut/Output modules with built-in signal conditioning, which can be directly connected to a wide range of sensors and actuators. In this system (Figure 3), cRIO performs averaging, FFT analysis, windowing, peak and fault detection analysis. The data transfer has been executed effectively through the network port. However, read/write instruction, execution time-critical loop tasks, reading data from motor has been carried out by FPGA module. The AI module is employed for capturing vibrations, voltage, current and flux signals using suitable sensors and signal conditioning devices. A custom LCD display module is designed to provide an on-line fault detection and display. It mainly deals with various categories of machine faults and corresponding fault threshold levels.

5 SYSTEM COMPONENTS

The cRIO platform presents a small, rugged, modular, scalable hardware/software fusionarchitecture consisting of of an FPGA, a real-tme processor and isolated Input/Output devices [16]. It is a good system to be used in industrial applications.

The cRIO architecture has similarities with that of the desktop computing system but with FPGA plug-in boards. The floating-point processing module that can be programmed with LabVIEW is connected to the FPGA on the backplane through an internal Peripheral Component Interconnect (PCI) bus. The cRIO modules consist of conversion circuitry (for analog modules), electrical isolation, signal conditioning, allowing direct connection to sensors on the monitored motor.

Real-time system development is a multistep process that includes (i) programming, (ii) debugging, (iii) compiling, (iv) downloading and (v) deploying. LabVIEW Real-Time is a unique facility, as it creates advanced real-time applications but takes advantage of all the benefits of LabVIEW for Windows graphical programming environment. The execution speed of each component needs to be measured to ensure that they meet their expected performance standards.

LabVIEW™ software is used to program the condition monitoring system . The scan rate frequency, number of samples and resolution are specified in the data acquisition Virtual Instrumentation VI block. Power spectrum subVI performs FFT analysis of signals. Spectrum graph is displayed on the front panel of the system. This main VI as shown in block diagram Figure 4, procures data continuously from the specified channel and carries out the scaling of the data to appropriate engineering units. Then program performs windowing of the signal, and the averaged frequency measurement. The VI returns the frequency resolution and the period of the acquisition time.

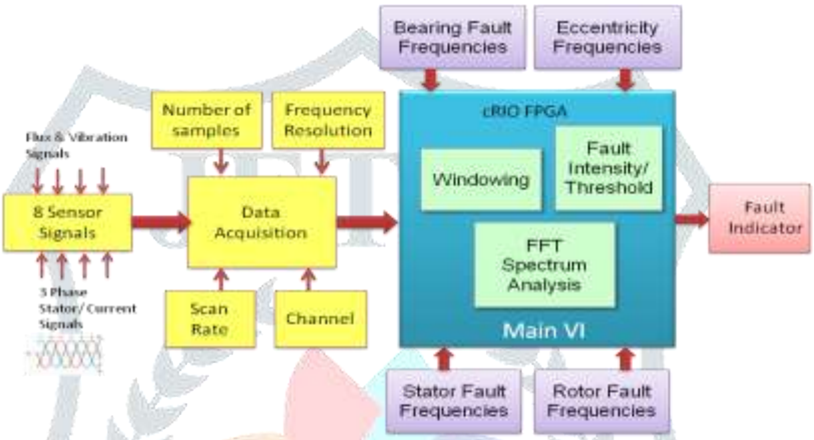


Figure 4 Block diagram of the Virtual Instrument Panel

The main Virtual Instrument panel comprises of subVIs for the identification of single and multiple faults. The cRIO condition monitoring system is used to detect stator shorted turns, broken rotor bar, eccentricity and bearing faults. Acquiring the 8-channel data & accomplishing anti-aliasing filtering, and transferring the data through DMA are executed by FPGA. FPGA also supplies data to the display module.

The data from the motor is analysied mainly in the real-time controller. The process sequence is initialisation of data, calibration of machine data from sensors, FFT analysis, peak detection of fault frequency components and averaging [15]. After the FFT analysis of motor, a number of subroutines are performed to detect exact faults based on the valid fault frequency equations.

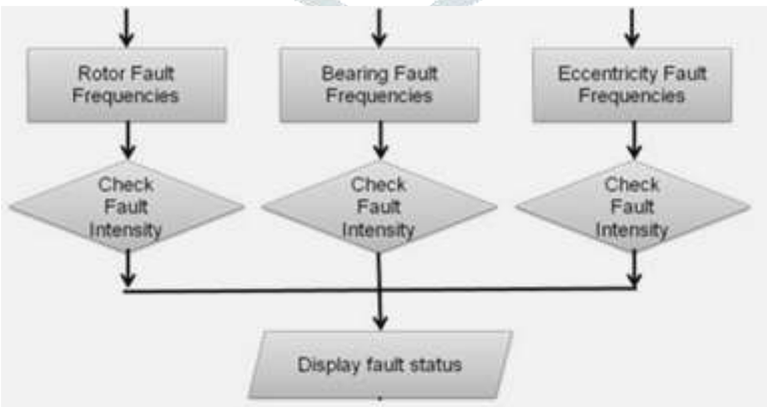


Figure 5 Part of the program flowchart showing different signal evaluation channels

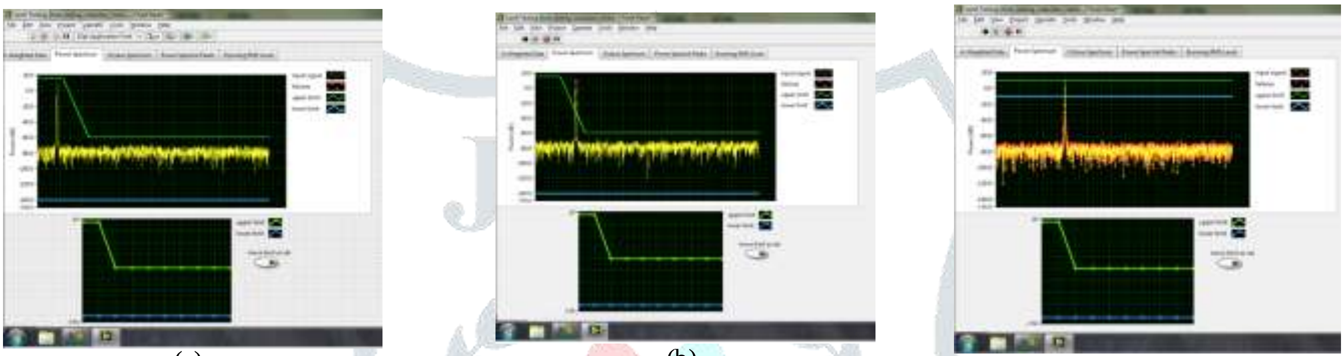
The algorithm for fault detection functions based on a threshold value for each parameter. Standard values are available, which provide the allowable levels of vibration intensities based on the motor size. They are empirically derived values for various fault frequencies and their intensities in the spectral analysis. For example, in stator current spectrum, if sidebands are less than -54 dB with respect to the main peak then the motor is considered healthy, if they are larger than -45 dB then the motor would be indicated as faulty with broken rotor bars.

A block diagram of the diagnosis system with different sensors and their positions are illustrated in Figure 4. The system monitors the motor continuously, using a set of current, voltage, flux and vibration sensors. If a fault is detected, the display module displays the fault type on an LCD panel.

6 EXPERIMENTAL RESULTS

To ensure the performance and to analyse the steady-state response of the condition monitoring system, various tests were conducted. The steady-state current, voltage, flux and vibration signals are obtained from the motor and are utilized to identify the multiple faults; The specifications of the induction motor under test considered is 4-pole, 415 V, 3 HP, 1440 rpm.

The implemented on-line condition monitoring system essentially identifies and detects the single and multiple mixed fault conditions. Using the cRIO embedded system, the prototype of Induction Motor fault detection system has been developed. Figure 6 presents the threshold limit testing process on front panel of VI (a) Normal (b) Crossing the threshold (c) Limit crossed. Fault magnitude threshold levels are specified in the program.



(a) (b) (c)

Figure 6 Threshold Limit testing process on front panel of VI:
(a) Normal (b) Crossing the threshold (c) Limit crossed

Figure 20 shows the FFT spectrum of $(1\pm 2s)f_s$ for the possible evaluations of the broken rotor bars, in which, the Fast Fourier Transforms (FFT) amplitude in range of 45Hz-55Hz, broken bar signals are shown. The other spectrum lobes can be detected, in addition to the fundamental signal, i.e., for eccentricity $\left(1\pm\frac{1-s}{p}\right)f_s$.; f_s .being the centre frequency.

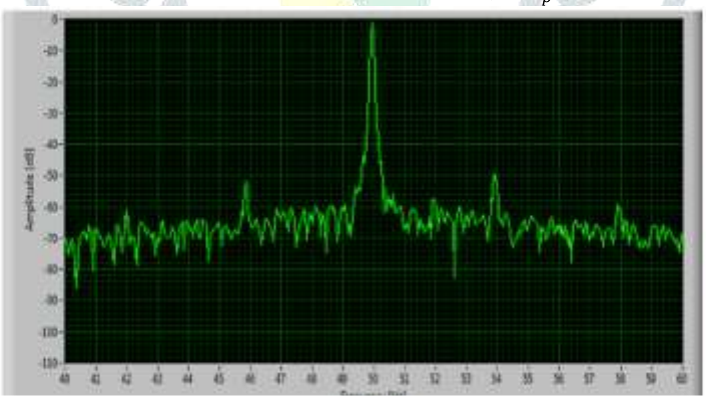


Figure 7 Identification of broken rotor bars of Induction Motor

7 CONCLUSIONS

An embedded system was implemented based on NI cRIO FPGA system, which has been tested for different performance parameters. The results obtained have indicated better performance even with varying operational parameters. Four fault types were considered in this work; viz., stator winding fault, broken rotor bars, bearing outer race fault and static eccentricity fault. The combined faults of broken rotor bars and eccentricity indicated precise results. The implementation of this system demands an immense initial learning curve. If this requirement is overpowered by the system developer, many more VIs with different algorithm strategies can be developed.

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