

Real-Time Remote Monitoring And Fault Diagnosis Of Induction Motors Using Labview

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Abstract : In modern industries, the most prevalent prime movers are induction motors. While these are sturdy in construction and extremely reliable, however, due to overloading, aging and excessive environmental and mechanical stresses, several faults may prematurely occur. Over time, numerous fault detection and diagnostic methods were developed for the initial phase inception of fault in induction motors. In this paper, a methodology based on the National Instruments (NI) Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) is discussed for real-time remote monitoring and detection of an early-stage stator Inter Turn Short Circuit (ITSC) and Broken Rotor Bar (BRB) faults in three-phase induction motors. The presence of faults was explored using well known Park's Vector Approach (PVA) and the Motor Current Signature Analysis (MCSA). The results obtained validate the feasibility of proposed methodology to effectively detect occurrence of faults in induction motors in real-time. The suggested methodology has a broad range of possible applications in the field of remote machine condition monitoring and will pave the path for researchers in the detection and classification of faults.

Keywords : broken rotor bar; fault diagnosis; induction motor; NI-LabVIEW; park's vector approach; stator inter-turn short circuit; web publishing tool (WPT)

I. INTRODUCTION

Robust nature, low cost, and simple operation are key features of Induction Motors (IMs), making them vital for the modern manufacturing industries. Squirrel cage motors are among the utmost used rotating machines, consuming about 85% of the total energy usage of manufacturing and engineering plants. However, during applications, these are subjected to many types of harsh environmental and operating conditions and are thus susceptible to failures like any other electromechanical device [1][2]. In recent decades, condition monitoring and fault diagnosis of rotating equipment have been the foremost subject of research in the scientific community. More specifically, considerable efforts have been made to diagnose the early stage fault development in order to reduce financial losses, maintenance costs, and production losses.

Conventionally, in industries the maintenance of electrical equipment follows two types of procedures: (1) fixed time maintenance, where the maintenance procedure is performed after a fixed interval, fully inspecting, overhauling and replacing different components of machinery, and (2) failure-oriented maintenance, where the maintenance activities are initiated only after the fault has occurred and the machine is no longer capable of performing further. However, recently introduced online predictive maintenance strategy helps in the planning of maintenance activities remotely and that too at right time such that the component life is maximized, maintenance expenditure is reduced, and catastrophic failures are avoided [3].

A significant amount of studies has been conducted over the past two decades to monitor and predict these motor failures at an early point of development. Early detection of faults not only helps to prevent abrupt motor failures but also helps to plan maintenance operations appropriately. This, in turn, helps to reduce maintenance costs and saves the motor from a complete breakdown. As a result, a large range of investigation methods were suggested in the literature [4]. The cost of wireless sensors, data acquisition, and analysis software is becoming economical and thus large amount of data collection, storage and inferencing has advanced, offering better and upgraded remote automated real-time condition monitoring. Hence over time, the maintenance of industrial motors has shifted from failure-oriented or time-based to sophisticated online predictive maintenance.

A. INDUCTION MOTOR FAULTS

Most of the induction motor faults start as a small defect and progresses over time into a severe fault causing abrupt stopping of motor operation or even fatal accident sometimes. Therefore, timely detection and remedial action are necessary to ensure the safety of the motor.

Induction motor faults are largely classified as mechanical and electrical faults.

- Electrical faults mainly include faults such as stator winding Inter-Turn Short Circuit (ITSC), Broken Rotor Bar (BRB), broken end-ring, and inverter failure.
- Mechanical faults include rotor eccentricity, bearing faults, shaft misalignment, gearbox and load faults such as load imbalance, etc.

Amongst the numerous types of flaws that can develop in an induction motor, bearing related (44%), stator (26%) and rotor (8%) related faults are the most common types of faults, especially in heavy industrial applications [3][5]. After bearing, the stator and rotor related faults are the most frequently occurring induction motor faults.

The presence of shorted-turns in stator winding generally has an untraceable effect on the motor performance, however, if left unattended for long, it may lead to a sudden motor breakdown. This type of fault usually originates primarily due to the insulation breakdown of the winding, leading to an ITSC fault which may eventually end in the development of serious stator winding failures such as coil-to-coil, phase-to-phase, or phase-to-ground fault, eventually resulting in complete motor failure [6]. There are numerous reasons which bring stresses on the stator winding of induction machines such as over-heating, vibrations, voltage unbalance and distortion caused by high switching frequency of adjustable speed drives, etc. The various techniques for stator winding fault diagnosis have been developed in the past years by researchers. A mathematical model-based induction motor fault detection technique has been imported in literature [7][8][9]. For stator winding fault assessment, in [7], the authors simulated the induction motor to study the behaviour of motor under no-load and loaded conditions. In [8], a transient model of an induction motor with turn faults in the stator winding was used, with the help of reference frame transformation. In [9], parameter estimation techniques were used for finding the stator and rotor faults. In [10], negative sequence impedance technique is employed for detection of stator fault whereas the higher-order spectra of a motor radial vibration are used to detect inter-turn faults in [11].

Another commonly occurring fault in an induction motor is the rotor fault, which can cause major motor damage if left unattended [12]. Rotor defects usually result due to broken bars or end rings, misalignment of rotor and imbalance. The most likely rotor faults, however, are the BRB and end rings. There are numerous reasons for rotor-bar and end-ring breakage such as thermal, mechanical, magnetic, environmental, and residual stresses. A number of techniques have been developed in the past for detection of BRB fault including rotor speed [13], vibration analysis [14], magnetic flux [15] and stator current monitoring [12] and PVA [16]. Vibration measurement [17][18], current analysis [19][20] or a mixture of both [21] are the most common techniques for detecting faults. Usually, these techniques use Fast Fourier Transform (FFT) computing to evaluate the signal to find fault-related spectral frequencies. However, due to low price and non-invasiveness, induction motor fault detection has now been carried out widely using electrical signals such as stator current and voltage rather than traditional techniques such as vibration, acoustic noise and temperature [22][23].

B. NI-LABVIEW

Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) has evolved over the past 30 years as a well-known programming language [24]. The LabVIEW is a proprietary software package offered by National Instruments (NI). It is a graphical programming environment for creating custom programs and virtual laboratory instruments. Programs written in LabVIEW are called “Virtual Instruments” (VI), consisting of ‘front panel’ and ‘block diagram’ for controlling and displaying the data and writing programs respectively. Using a number of inbuilt application-specific VIs, it can be used for data acquisition, storage, analysis, and presentation, etc. LabVIEW has a number of libraries, functions, and subroutines which are used for most of the general-purpose programming tasks [24], providing an accurate, simple and efficient way for designing data acquisition and signal processing platform for a variety of applications. It has a number of turnkey characteristics, making it a lucrative choice for control and automation purposes. The LabVIEW includes hassle-free network communication with the implementation of popular data transfer protocols like GPIB, RS232, USB, etc., strong process control and data fitting tools, quick and easy development of user interfaces, and an effective code execution environment. Numerous researchers used LabVIEW for fault detection and diagnosis in three-phase induction motors [24][25][26].

In the present work, the motor faults are artificially created to study their effect on motor signals such as voltage, current, and vibration. Data is acquired from the motor with known faults and algorithms are developed to characterize and isolate each fault state from the healthy motor condition. A NI-LabVIEW based fault diagnosis approach using Motor Current Signature Analysis (MCSA) and Park’s Vector Approach (PVA) is used for IM fault detection. A specially made software routine is used to acquire, analyse and monitor the real-time signals from a three-phase induction motor using Web Publishing Tool (WPT), for recognition of possible fault occurrence.

II. MOTOR CURRENT MONITORING

Numerous techniques for identification of faults in induction motors have been developed in the past, the most popular ones are based on vibration and stator current monitoring [5][7][8]. Although vibration-based monitoring is one of the most popular methods of condition monitoring, however, it suffers disadvantages such as high cost of sensors and the requirement of sophisticated signal conditioning of sensor signal, etc. On the other hand, current monitoring, also popularly known as MCSA, is a non-contact, economical and simple to implement a method of fault diagnosis. A number of signal processing techniques can be applied to the acquired stator current such as FFT, PVA, STFT, wavelet analysis, etc. to evaluate the health of induction motors [8][10]. The brief description of MCSA and PVA is given in the subsequent sections.

A. MCSA

One of the earlier methods for fault detection in a three-phase induction motor was the spectral analysis of motor current also popularly known as MCSA. In this method, usually, a single-phase current is acquired either

directly or using a current transformer and Fourier transform is applied to observe the spectrum for the presence of fault-related components. This method offers a convenient way of observing various types of motor faults. The spectral analysis based on MCSA is the most widely accepted method for the detection of BRB fault, owing to its low cost and non-invasiveness [12]. The spectral analysis relies on Fast Fourier Transform (FFT) of stator current, where the occurrence of a fault is reflected in the rise in the magnitude of the so-called sideband harmonics, given by [27]:

$$f_{brb} = (1 \pm 2sk)f_s \quad (1)$$

where, 's' is the slip, f_s is the supply frequency and $k = 1, 2, 3, \dots$

The lower sideband harmonic occurs due to the BRB, whereas upper sideband harmonics are dependent on subsequent speed variations. The magnitude of sideband harmonics is formed to be directly related to the number of BRBs and motor loading. For a fully loaded motor, a difference of approximately 35-40 dB from the fundamental is a clear indication of the presence of a BRB fault. The magnitude difference of less than 30 dB indicates the presence of multiple BRBs in the motor [27]. However, this method suffers from limitations due to low spectral resolution and the inability to analyze non-stationary signals. Moreover, these sideband harmonics are slip dependent and thus an accurate estimation of slip is a must for successfully applying this method.

Apart from the characteristic sideband harmonics given by expression (1), another set of distinctive sideband frequency components are also observed in the spectrum, given by [2][4]:

$$f_{sideband} = (f_s \pm f_r) \quad (2)$$

where, f_r is rotor's mechanical speed in revolutions per second.

These harmonic components mainly occur due to rotor asymmetry or the eccentricity problem [6]. Eccentricity fault is caused when the rotor's rotational axis differs from either the stator bore axis or the rotor's geometrical axis [4]. Eccentricity may be a result of improper motor design, poor installation or damaged bearings, etc. A small amount of eccentricity may exist and is permitted in motors considered perfectly healthy.

Faulty rotor's due to faults such as BRBs, eccentricity, rotor misalignment etc. usually causes excessive vibrations, torque oscillations, poor starting torque and higher thermal stress, resulting in the elevated magnitude of $(f_s \pm f_r)$ frequency components. Thus, the relative increase in magnitude of sideband frequency components, (2) compared to that of healthy state may indicate the rotor asymmetry due to BRBs.

B. PARK'S VECTOR ANALYSIS

The Park's vector approach for stator fault detection uses three-phase motor currents and transforms them into Park's vector components i_d and i_q , i.e., direct axis and quadrature axis currents. Park's vector transform is used to describe three-phase induction motor currents, i.e. (i_a, i_b, i_c) into a two-dimensional representation [28]. It is a vector locus produced by spatial addition of the three-phase stator currents. Park's vector locus is mainly affected by the presence of motor faults such as ITSC, voltage unbalance and air-gap eccentricity. The Park's vector components are given by:

$$i_d = \sqrt{\frac{2}{3}}i_a - \frac{1}{\sqrt{6}}i_b - \frac{1}{\sqrt{6}}i_c \quad (3)$$

$$i_q = \frac{1}{\sqrt{2}}i_b - \frac{1}{\sqrt{2}}i_c \quad (4)$$

For a perfectly intact motor, a plot between i_d and i_q draws a circle representation centered at origin. A deviation from an ideal circular pattern can be used for detection of abnormal motor conditions such as stator turn fault, BRB and current imbalance etc. PVA has been extensively used in the past for fault diagnosis applications such as detection of unbalance in stator voltage and bearing faults [29].

III. METHODOLOGY

For predicting the status of stator and rotor from the motor signal measurements such as vibration, current and voltage, a new autonomous approach is proposed based on NI-LabVIEW. LabVIEW is a development environment devoted to working with data acquisition and control using hardware, it significantly decreases development and integration time, enhances overall efficiency and reliability. It is based on graphical programming, where users can use software objects to create virtual instrumentation tools. These virtual tools can be used with appropriate hardware to remotely acquire, analyze, design and control data. VIs constructed using LabVIEW are simple to control and share on the internet as LabVIEW has a range of VIs such as Data Socket server, VI server and Active X, Visual Basic, Java and Java Script that can be used to design and create virtual tools that are enabled on the internet [30]. A variety of internet-based applications has been implemented using LabVIEW like [31]:

- Development of VIs for real-time multiple user cooperation.
- Development of e-commerce websites and web-server applications.
- Development of virtual educational laboratories for remote student access.

Also, there are several examples of internet-based VIs developed, which are low-cost and user friendly, for applications such as: remote control and monitoring and distributed computing applications [32]. This innovative technology can efficiently detect for any abnormality in the running motor [29].

A. WPT FOR REMOTE MONITORING AND FAULT DIAGNOSIS

Since LabVIEW launched real-time engine and remote panels used to view or control VIs from web browser, the users can run an application from far-off. Also, several operators can simultaneously access the same VIs from distant places [32]. However, to accomplish this, users should have following requirements fulfilled [33]:

- 1) client/ user device needs LabVIEW real-time installed.
- 2) server device must have LabVIEW software installed with multi-user licence for LabVIEW real-time and front panel.

Fig. 1, shows the scheme of the motor fault monitoring and diagnosis framework. The details of publishing the fault detection VI via Web Publishing Tool (WPT) is available in [30].

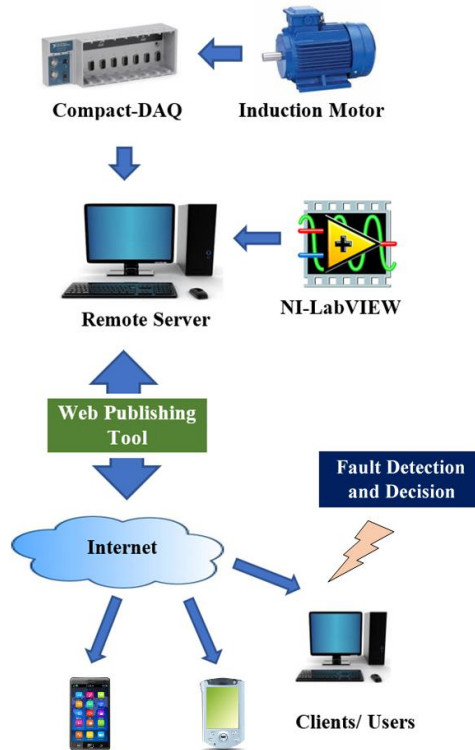


Fig. 1. Remote Monitoring and Fault Diagnosis Using Web Publishing Tool

This tool generates a Hypertext Transfer Protocol (HTTP) Uniform Resource Locator (URL) address for accessing the VI using browser. The LabVIEW WPT produces the html code needed to display the VI output in the browser when the generated HTTP URL is provided as the browser's address. This URL also includes system Internet Protocol (IP) information making it available on the Local Area Network (LAN). The browser page being a local file, displaying only the front panel of VI is available on the same computer on which the VI is generated and saved or the devices on the same LAN. For the file to run, the LabVIEW software and extensions are required. To allow the VI to be accessed and controlled remotely, the computer must have a public IP, turning it into a server that can be accessed either locally or remotely on any device. As stated above, some supporting software/plugin are required to access the VI remotely via the Internet (using the HTTP URL) and for browser compatibility as per the user's browser platform, such as the LabVIEW Run-Time Engine (RTE).

Fig. 2 shows the methodology followed for NI-LabVIEW based real-time detection of the stator ITSC and BRB faults in induction motors. The current, voltage and vibration data was acquired using NI-based data acquisition system and signal processing tools were used to apply FFT and Park's vector transformation on motor current. Fault detection was carried out at different loading conditions of induction motor for varying fault severity. Thus, data was acquired from motors operating under steady-state conditions.

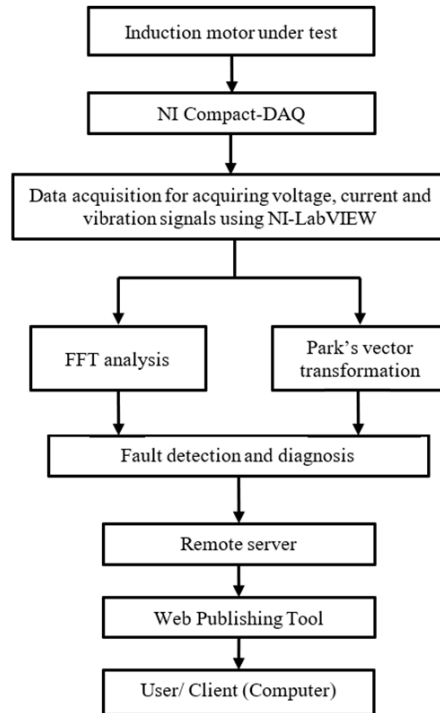


Fig. 2. Methodology for Real-Time Motor Fault Detection using NI-LabVIEW

IV. PRACTICAL IMPLEMENTATION

A three-phase, half-hp, four pole, star connected induction motor was used for detection and diagnosis of BRB and stator ITSC faults. The complete experimental setup experimental setup for data collection is shown in Fig. 3.

The BRB(s) and inter-turn short-circuit faults were implemented artificially in the motor under test. To realize the stator ITSC fault, motor under test was rewound. The motor winding was such that, each phase contained four coils and each coil had 147 turns. For shorting the winding turns, connections were carefully taken out after 13th, 23rd and 30th turns of the same coil. The BRB faults were realized by drilling out one and three consecutive bars respectively from the rotor, as shown in Fig. 4. The drilled holes were enough in diameter and depth, so that the bars were completely removed.

Signal measurements from motor were obtained using data acquisition system comprising of NI-cDAQ-9178, NI-9244 and NI-9227 voltage and current sensing modules along with NI- 9234 module for vibration sensing. To acquire the vibration signal from motor, a single axis accelerometer (sensitivity: 100mV/g) was placed rigidly on the motor's bearing housing on the drive end.

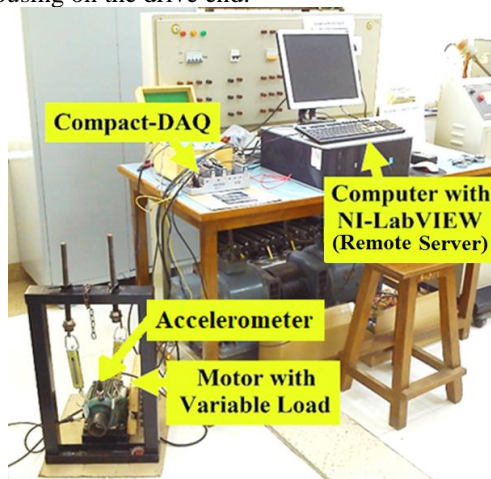


Fig. 3. Experimental Setup used for Motor Testing



Fig. 4. Artificially Created Broken Rotor Bars

For monitoring and fault diagnosis purposes a specially designed VI is used for viewing the operating motor conditions. The VI front panel is shown in Fig. 5. The VI front panel consists of displays for three-phase voltage, current and vibration waveforms; displays for frequency spectrum of vibration and current and display for Parks’s current vector locus.

The current’s Park vector is computed using the expressions, (3) and (4) and displayed using X-Y waveform graph. Here, the motor is assumed to be operating under steady-state conditions. There is also provision for saving the acquired data in the computer’s memory, to be further examined using advanced signal processing for fault detection and classification. The VI can help diagnose the electrical faults namely, stator and BRB faults in induction motors online and real-time. Using WPT, the diagnosis can be made from a distant point from the motor installation. Here, NI-LabVIEW has been employed for software implementation on both client and server side. Fig. 6 shows the client side web-page showing the real-time condition indicators for an operating induction motor.

Initially, a total of 48000 samples were acquired continuously for each channel at a sampling rate of 12800 samples per second. This way, a frequency resolution of 0.26 Hz (12800/48000) was obtained for FFT initially. However, due to practical reasons and for reducing computational load, the sampling rate for data acquisition was selected as 3200 samples per second with total number of samples to be acquired as 16000. Thus, the displays for acquired waveform were refreshed after every 5 seconds interval.

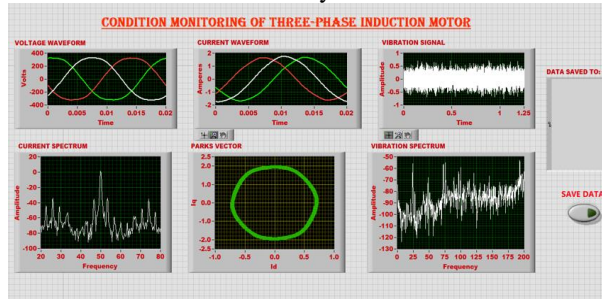


Fig. 5. Front Panel of VI used for Condition Monitoring

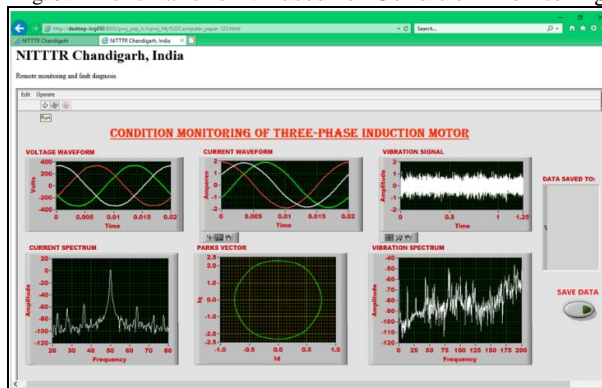


Fig. 6. Client-side web-page showing Motor Parameters for Remote Fault Monitoring.

V. RESULTS AND DISCUSSION

The following section explains the results obtained from tested motors operated under different fault conditions and loads. The induction motor with varying number of shorted turns and BRB condition, was run at different loading conditions for comparison. However only the results for no-load and full-load conditions are considered here to get a better insight of the loading effect on fault detection.

A. STATOR INTER-TURN FAULT DIAGNOSIS

Fig. 7 (a)-(d), shows the results obtained by applying Park's vector analysis. From the results, it can be observed that in case of healthy motor, the Park's current vector draws nearly a perfect circle for both the no-load and full-load conditions.

However, as the number of shorted turns increases, Fig. 7 (b)-(d), for both loading conditions, the Park's vector changes in shape from being a perfect circle towards an elliptical pattern. It was observed that, more the number of turns were shorted, more was the shape distortion. Also, for both no-load and full-load conditions, the pattern observed is similar, however for full-load case the shape distortion as well as the thickness of the locus is slightly more as compared to no-load case. Thus, it can be deduced that, the stator inter-turn fault can be easily identified for no-load as well as full-load conditions.

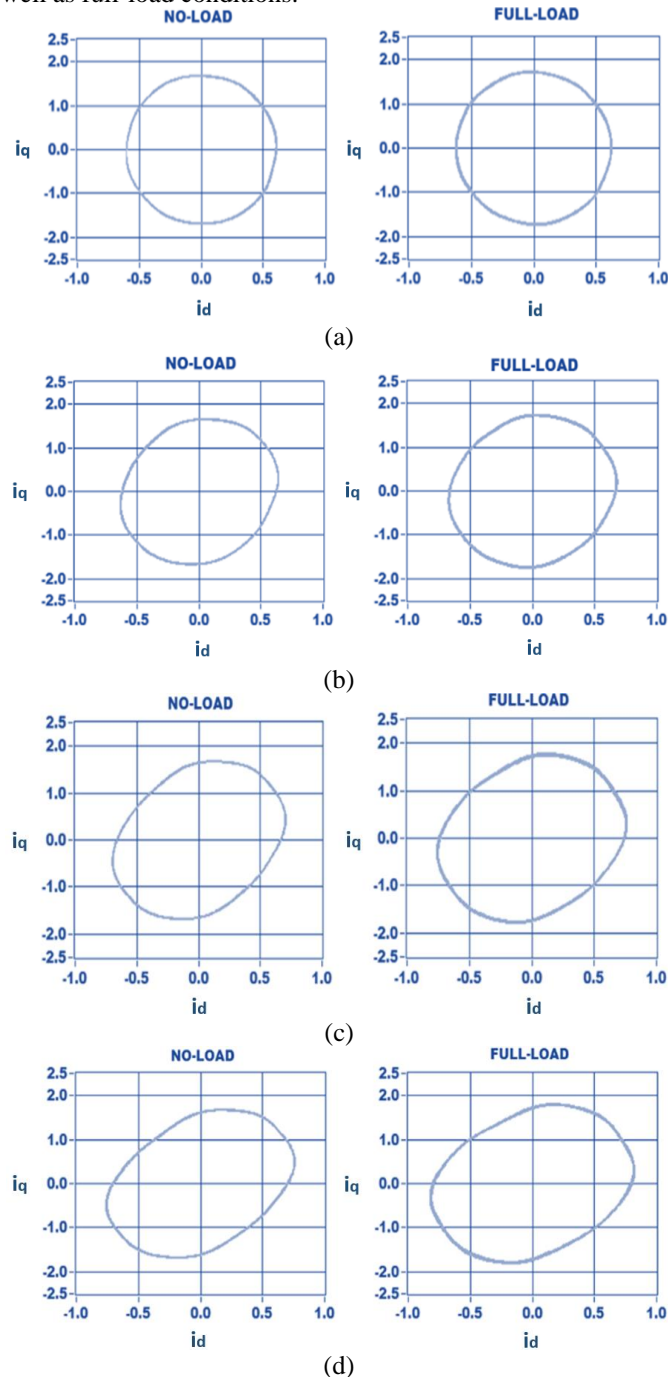


Fig. 7. Park's vector locus for different motor conditions (a) healthy, (b) 13-turns, (c) 23-turns, (d) 30-turns shorted.

B. BROKEN ROTOR BAR DETECTION

For identification of BRBs, FFT was employed to plot the current spectrum of induction motor. Also, the Park's vector approach was used to find the effect of fault severity and motor loading on its locus.

1) No-Load Condition: The Fig. 8 (a)-(b) shows the current spectrum and park's vector circle for motor with 1-BRB and 3-BRB faults at no load condition. As seen, the sideband harmonics at twice the slip frequency given by the expression (1), i.e. $(1 \pm 2s)f_s$, typical for BRB condition were insignificant in amplitude and undistinguishable. This is because, the slip in this case is of very small value and thus, the sidebands merge into the main fundamental lobe.

Another type of harmonic components, given by expression (2), i.e. $(50 \pm f_r)$, are however clearly visible in both the cases, with the magnitude being more significant in case of 3-BRB fault. This may be attributed to the uneven current flow in the rotor due to the presence of BRBs, causing torque fluctuations and thus producing the said sideband harmonics. However, these are the same harmonics observed for eccentricity problems and therefore cannot be explicitly regarded as BRB fault indicators.

Also, as observed for 1-BRB fault at no-load, the Park's vector circle draws perfectly and thus shows no sign of failure. However, in case of 3-BRB condition, Fig. 8(b), the Park's vector circle has a thicker periphery. For a motor operating in steady state conditions, this thickening is caused due to the presence of higher magnitude of sideband components, thus, prominently indicating the presence of some rotor abnormality.

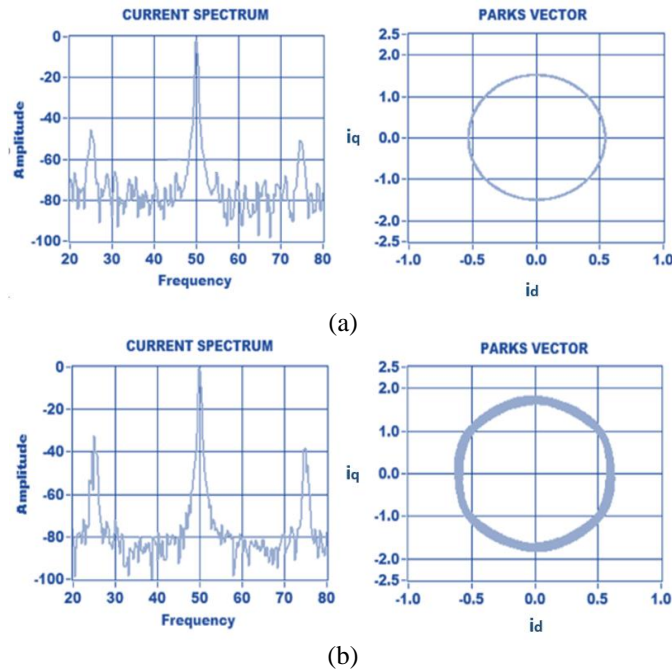


Fig. 8. Motor at No-load with (a) 1-BRB (b) 3-BRB fault

2) Full-Load Condition: In Fig. 9 (a)-(b), the motor spectrum and Park's vector circle are shown for full load conditions of 1-BRB and 3-BRB. The current spectrum for 1-BRB fault at full-load condition shows a significant increase in $\pm 2sf_s$ harmonics as compared to no-load case; the difference of magnitude from fundamental component being nearly 40 dB. It can be perceived as a clear indication of presence of at least one BRB. In full-load condition with 1-BRB, the $f_s \pm f_r$ components were also higher in magnitude as compared to no-load condition. The significant increase in magnitude of both these sideband components cause amplitude modulation of stator current, which becomes evident in Park's circle pattern, causing broadening of its locus.

Fig. 9 (b) shows motor having 3-BRB fault at full-load condition. As seen, here the $\pm 2sf_s$ sideband harmonics are prominent and clear with their magnitudes nearly -35 dB, indicating the presence of multiple broken rotor bars in the motor. The magnitude of $f_s \pm f_r$ components in case of 3-BRB remains almost same as for 1-BRB, however, a larger number of sideband harmonics become prominent and visible near the rotor speed harmonics, i.e. the $f_s \pm f_r$. It was observed that, for 3-BRB fault, the Park's vector locus becomes thicker like in the case of 1-BRB, however it shows further distortion. This may be attributed to a greater number of different sideband components (with significant magnitudes), causing a higher amount of amplitude modulation of stator current.

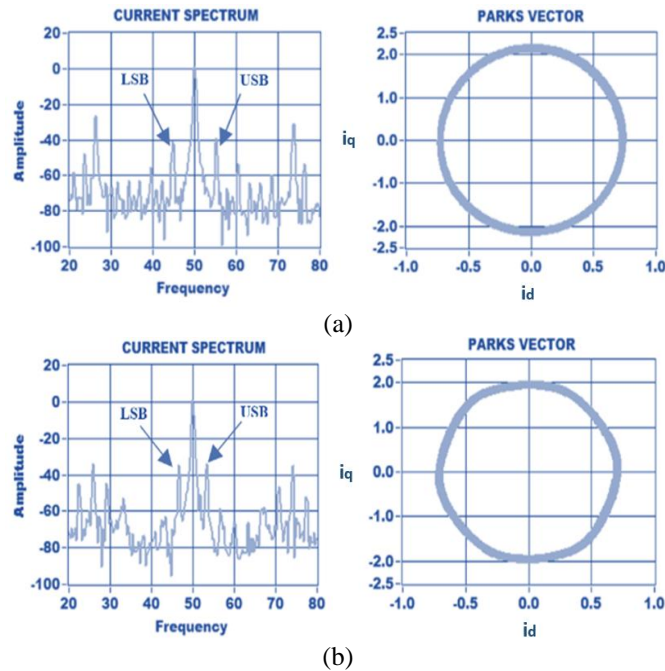


Fig. 9. Motor at Full-load with (a) 1-BRB (b) 3-BRB fault

VI. CONCLUSION AND FUTURE SCOPE

In this paper, NI LabVIEW based data acquisition and fault analysis was carried out in real-time to diagnose the stator ITSC and BRB faults in three-phase induction motor under different loading conditions. The fault diagnosis has been carried out using current based spectrum analysis and Park's vector approach. The MCSA and PVA results were successfully able to diagnose the BRB and ITSC fault conditions.

As seen from results, it can be concluded that for detection of BRBs, a careful examination of both PVA along with current spectrum observation is necessary for assuring the presence of BRBs. Whereas, the ITSC faults can be easily diagnosed using Park's vector locus, provided the supply voltage is balanced and the motor is under steady state operation. Also, for ITSC fault detection using Park's vector approach, the loading condition is not that significant as for BRB fault detection.

The results obtained were promising and were able to successfully diagnose the motor conditions. Further, using the WPT, the fault diagnosis capability has been expanded to remote locations. This type of approach for fault detection and diagnosis presents a convenient medium for detection of a variety of faults for applications such as condition monitoring of transformers, Gearbox and other industrial machinery. As a future work the proposed system can be integrated with wireless sensor networks and IoT for remote monitoring and cloud-based diagnosis and generating alerts regarding equipment condition. Also, advanced signal processing and fault detection algorithms such as STFT, Gabor transform, and wavelet analysis can be used for time-frequency analysis of non-stationary signals. Furthermore, the traditional condition monitoring techniques are enhanced with the introduction of new paradigms such as wireless sensor networks, big data analytics, IoT and cloud computing accompanied by development of advanced signal analysis techniques.

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