MAGNETIC FIELD ANALYSIS FOR HEALTH MONITORING OF INDUCTION MOTOR USING SEARCH COIL

THESIS

submitted in fulfillment of the requirement for the degree of
DOCTOR OF PHILOSOPHY

to

J.C. BOSE UNIVERSITY OF SCIENCE & TECHNOLOGY, YMCA, FARIDABAD

by

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SEPTEMBER 2021

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CANDIDATE'S DECLARATION

I hereby declare that this thesis entitled **"MAGNETIC FIELD ANALYSIS FOR HEALTH MONITORING OF INDUCTION MOTOR USING SEARCH COIL"** by **PRIYANKA** being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in ELECTRONICS ENGINEERING under Faculty of Engineering and Technology of J.C. BOSE University of Science and Technology, YMCA, Faridabad during the academic years 2012-21 is a bona fide record of my original work carried out under guidance and supervision of **Dr. NEELAM TURK**, **PROFESSOR**, **DEPARTMENT OF ELECTRONICS ENGINEERING,** J.C. BOSE UNIVERSITY OF SCIENCE AND TECHNOLOGY, YMCA , FARIDABAD and **Dr. RATNA DAHIYA**, **PROFESSOR, ELECTRICAL ENGINEERING DEPARTMENT,** NIT KURUKSHETRA, HARYANA and has not been presented elsewhere.

I further declare that the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or any other university.

(PRIYANKA)
Registration No. - **YMCAUST/Ph 25/2K11**

CERTIFICATE

This is to certify that this Thesis entitled **"MAGNETIC FIELD ANALYSIS FOR HEALTH MONITORING OF INDUCTION MOTOR USING SEARCH COIL"** by **PRIYANKA** being submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in **ELECTRONICS ENGINEERING** under Faculty of Engineering and Technology of J.C. BOSE University of Science and Technology, YMCA, Faridabad during the academic years 2012-21, is a bona fide record of work carried out under our guidance and supervision.

We further declare that to the best of our knowledge, the thesis does not contain any part of any work which has been submitted for the award of any degree either in this university or in any other university.

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Abstract

Induction motor undoubtedly has an important role in the industry on account of their benefits over other electrical motors. Consequently, there is a strong requirement for their consistent and reliable operation. If any defect and failures take place in the motor it could result in unnecessary downtimes and bring about great losses with regards to revenue and maintenance. Hence, early fault detection is considered essential for the safety of the motor. The research work presents a broad view of the fault indicators generally employed for finding defects in motors, with a special interest on electromagnetic flux monitoring, as the current study depends on the indications given by these parameters. In the present circumstances, the health or condition monitoring of the induction motor are progressively increasing on account of its prospective to lessen operating costs, improve the consistency of operation and enhance service to the customers. The faults executed in the motor's structures and their modeling processes are presented. A specification of the measurement system employed for the validations of the findings acquired from experimental setup and optimization are employed in the field of fault identification in electrical motors is as well to be found in this work. With increasing demands for consistency and effectiveness, the field of fault analysis in induction motors is receiving lots of importance. If the defects are not predicted in advance, it might bring about large revenue losses and also create threat to consistency and safety of operation. Though, many techniques have been recommended for fault detection and analysis, but the majority of the techniques demand a good deal of knowledge to implement them effectively. Simpler approaches are required to facilitate even unprofessional operators with minimal knowledge of the system to detect the defect condition and make appropriate decisions.

The research work deals with condition monitoring and emphasized that with the application of condition monitoring, it is quite practicable to give adequate notification of failure, which is about to happen. The condition monitoring and fault detection or diagnosis method permits the operators to have essential unused parts before the motor is stripped down, thus lessening outage times. Though there is a large number of condition monitoring and diagnostic techniques for other defects, researchers are looking for a simple and uncomplicated way to monitor gearbox fault, which is considered significant power transmission element in any machinery. Further, at times, analysis of vibration in the gearbox is uncomplicated on account of the detachment in mounting the vibration transducers. Laboratory experiment has been carried out to diagnose different faults including gearbox, air-gap eccentricity broken rotor bar fault.

The research work presents an in depth analysis of detection trough experimental setup and diagnosis trough Particle Swam Optimization (PSO) and Modified Particle Swam Optimization (MPSO) of these faults and recommends future research areas in the same field. An effort is taken to assess internal and external fault detection techniques taking recently used optimization techniques, artificial intelligence based, signal processing and hybrid techniques into account. The field of health monitoring identifies those problems, and current study is contributed to it by discussing several related problems. All of the induction motor defects are not identified in its initial stage and late awareness of these defects will cause to lose tolerance to certain extent. Therefore, fault identification and diagnosis in induction motors have increased importance for maximum industrial activities. The research work puts forward that diagnosis of motor defects in advance is a fundamental pillar in order to accomplish complete tolerance by the maintenance of defective parts in motors. The FFT examination of magnetic flux of healthy induction motor and unhealthy induction motor has been achieved through hardware setup and so Particle Swarm Optimization (PSO) and Modified Particle Swarm improvement (MPSO) are used for parameter approximations. The experiments are completed on 1.5kw, 440V, SEW EURODRIVE induction motor and parameter assessment is finished through MATLAB/Simulink.

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List of Abbreviations

AI	Artificial intelligence
ANFIS	Adaptive Neural Fuzzy Interference System
ANN	Artificial Neural Network
BRB	Broken rotor bars
CBM	Condition-based maintenance
CMS	Cyclic Modulation Spectrum
DC	Direct Current
DWT	Discete Wavelet Transform
FDA	Fault diagnosis analysis
FEA	Finite Element Analysis
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
FSA	Flux signature Analysis
GMM	Gaussian Karma Models
GR	Generalized Roughness
IM	Induction Motor
MCSA	Motor Current Signature Analysis
MMF	Magneto-motive force
MPSO	Modified Particle Swarm Optimization
MRWA	Multi-resolution wavelet analysis
MUSIC	Multiple Signal Classification
NN	Neural networks
OCM	Operating condition monitoring
PSD	Power Spectral Density
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation
RMS	Root Mean Square
SV	Space Vector
SFFT	Short Freuency Fourier Transform
SPTs	Signal Processing Tools

List of Abbreviations

SSWF	Sparsity Based Wavelet Feature
STFT	Short Time Fourier Transform
TBM	Time-based maintenance
TMCSA	Time Motor Current Signature Analysis
TSFE	Time stepping finite element
UMP	Unbalanced Magnetic Pull
WT	Wavelet Transform
WPD	Wavelet packet decomposition
ZSC	Zero Sequence Current

Chapter 1

Introduction

1.1 Overview

Induction motor is one of the most globally used electro-mechanical device particularly in the industrialized based processes in order to convert electrical energy into mechanical energy. As a result of its resilient characteristics such as strong, flexible, control in various applications, the implementation of induction motors in industrial purpose is extreme to a large extent. Owing to the large range of categories, applications, and faults of induction motors, the focal point of this discussion will be given on fault detection of induction motors studied in this study. On the whole, induction motor faults are classified into electrical and mechanical. Also, fault detection at initial stage is one of the major issues to be considered. Accordingly, to detect an initial stage fault, special attention to the induction fault diagnosis is given.

The constant health check of the equipment all through its service life is generally termed as health or condition monitoring. And it is considered extremely substantial to find faults whilst they are still developing. The condition monitoring of the induction motors provides a constant review of the electrical condition of machines. With the application of health monitoring, it is quite practicable to give adequate notification of failure, which is about to happen. Consequently, it is possible to plan for future preventive repair work, which could result in the least downtime and most favorable maintenance plans.

The condition monitoring and fault detection or diagnosis method permit the machine operators to have essential unused parts before the motor is stripped down, thus lessening of outage times. Therefore, [1] stated that efficient health monitoring could enhance the reliability, safety, and efficiency of the motors. The magnetic flux monitoring and voltage techniques had been used previously, which actually demanded costly sensors. Induction motors have an important role in industrial processes since they are strong and flexible in their construction. Though, an intrusion of an industrialized process on account of a failure in an induction motor could stimulate a major financial set for the firm. As stated by [2] it is considered essential to find out a faulty state and stop its growth, before giving rise to tragic failures. For this cause, the initial detection of the motor fault is extremely essential.

Amongst the number of faults, rotor faults represent almost around 10% of overall induction motor failures. Broken rotor bars (BRB) can be an important setback to be considered while induction motors should execute hard duty cycles. In general, BRB bars do not primarily make an induction motor to fail, however, they could give rise to critical mechanical impairment to the stator windings once they are left unnoticed. In addition an induction motor with BRB could not function in dangerous settings as a result of sparking at the defective site. [3] pointed out the techniques more effective in finding out rotor faults are largely on the basis of analysis of stator currents with the application of algorithm known as Fast Fourier Transform (FFT).

Mechanical mechanisms that are in action in an induction motor are specifically creating problems from wear and tear, deterioration, corrosion, low energy, exploitation, etc. Electrical systems are likely to be affected by wear, corrosion, the maturity of plastic components, waste contamination, terminations becoming loose-fitting, etc. Generally, electrical and mechanical faults are considered as two types of induction motor faults. Bearing the problems that are considered as the major source of induction motor failures, nearly 40-50% of motor defectiveness is bearing based. Various factors have an extreme impact on the lifetime of bearing, which is as follows: on account of uneven air-gap which involves the stator and rotor, static air-gap eccentricity will emerge. In terms of dynamic eccentricity, when the centre of both dynamic eccentricity and rotor are not with similar axis later the smallest possible air gap revolves with the rotor. [4] pointed out that a broken bar causes various effects in the induction motors. A well known effect of a broken bar is the appearance of the sideband component. Induction motors are considered essential components in productively available types of equipment and engineering or manufacturing processes as a result of commercial and strong performance. The modern manufacturing process are greatly relying on the usage of Induction motors and drives. They have now become the backbone of almost all the industrial setup.

Within numerous operating stresses, motors weaken their conditions that actually give rise to various defects. Detection in its early stage and diagnosis of these defects are considered necessary for online condition appraisal, product quality assertion and enhanced operational effectiveness [5]. The induction motor is considered comparatively simple and includes two major parts: the stator and the rotor. Besides, comparatively, the induction motors employed in the industrial field are largely three-phase than DC or single-phase on account of its various characteristics such as smaller, lighter, cost-effective and have a least starting current. Various factors resulted in the corrosion conditions of an electric motor and the rate of numerous types of defects. For this cause, the defects of the electric motors could be categorized from various viewpoints, such as temperature, aging, vibration, overall, quality, bad use, ventilation, manufacturing defects, inappropriate or poor quality parts, etc. It is [6] stated that some of the benefits of predictive maintenance, which are as follows: reduction of maintenance costs produced by a breakdown, reduce redundant maintenance actions and register the actions of the machine, etc.

Though protective and corrective repairs have largely been used, on account of technological growth, flexibility and economical, the trend is transforming. Predictive maintenance for the initial detection of mechanical and as well as electrical defects on the basis of the review of frequency spectra employing artificial intelligence methods have been executed more often. A number of condition monitoring techniques have been recommended for various kinds of induction motor fault detection and localization. In general, large electromechanical components are protected with mechanical sensors, largely vibration sensors for the identification of the defects [7].

Condition monitoring and early fault diagnosis of induction motors play an important role in production lines, which could considerably lessen the maintenance cost and the possibility of unpredicted failures by facilitating the initial detection of likely catastrophic faults. One of the most standard and precise techniques for finding faults in induction motors is presently the Motor Current Signature Analysis (MCSA) [8]. Failure of induction motor might give rise to plant shutdown and raw material wastage which results into huge monetary and opportunity loss. Thus, it has become vital to keep a regular check on the overall functioning of the plants and the machines.

The monitoring, detection, and analysis of the motor conditions could be performed whilst the machine is operating by employing the current and voltage transformers applied in the protection system. MCSA integrates parametric analysis techniques, non-parametric techniques, and better resolution or sub-space methods. Once the signal is not static, analysis methods are largely on the basis of higher-order spectral analysis, for example, bi-spectrum and tri-spectrum, and higher-order numerical techniques to acquire the intensity of the frequency spectrum [9].

Mechanical stresses are generally produced by overloads and sudden load changes that might result in bearing faults and rotor bar breakage. The electrical pressures might create stator winding short circuits and cause entire motor failure. Bearing failures are approximately responsible for about two-fifths of all defects. Inter-turn short circuits in static windings characterize nearly one-third of the listed defects. BRB and end ring faults stand for about 10% of the induction motor faults. Condition monitoring of the functioning of induction motors gained substantial attention in recent decades[10]. These vibration sensors are considered attractive but high-priced. The stator current monitoring could impart the same signs without necessitating access to the motor. This method generally uses the effects of spectral analysis of the static current of motors to identify the failure of the induction motors [11]. The most generally employed fault-based feature extraction methods are Fourier spectral analysis by FFT, bi-spectrum, high-resolution spectral analysis, and Artificial intelligence techniques [12].

MCSA of the stator current with a wavelet to find the defect in a BRB in the temporary region has been carried out by [13]. The assessment of the sensorless control technique of induction motor with a BRB for diagnostics employing wavelet methods has been given by [14]. This [15] dealt with a unique condition to find out the BRB employing time stepping finite element (TSFE) to develop the BRB in an induction motor. The work by [16] investigated a novel technique to find out the rotor broken bar employing Ridge wavelet. [17] presented FFT as a spectral analysis technique with the TMCSA in order to identify the rotor broken bar. [18] employed FPGA to find out a number of defects in the squirrel cage, for example, unstable, defective bearing and broken bars employing parallel structure of fused fast Fourier transform (FFT) and wavelet. Some issues have been observed to feature in the usage of the MCSA technique for fault detection, particularly once the load torque differed. The disadvantages of applying FFT, such as corrupted frequency elements, the noises or other occurrences, for example, load torque variability or supply voltage fluctuations [19].

Induction machines represent the mainstream of industrial tools in operation these days and appropriate operation is of greatest significance. The application of wavelets for induction motor fault identification is registered in a large number of journals [20]. They have been proven to produce satisfactory results for finding electrical and mechanical defects. In general, the field of induction machine fault identification has been on the basis of the usage of the FFT. The application of FFT-based motor fault identification demands that frequency resolution to be very good, usually lower than 1 Hz. To accomplish this better resolution, it is important for the dataset to be very large and consequently necessitates a huge amount of memory for further processing [21].

The first techniques used to find motor failures, for example, chromatographic analysis, temperature, and vibration analysis, have been progressively transforming to new on-line monitoring methods for electrical equipment. One of these innovative techniques is the observing of the stator current. Wavelet decomposition is considered as one of the superior techniques of signal assessment in time-varying conditions as a result of spatial data maintenance. Analysis employing wavelets creates both frequency and spatial information giving a healthy solution for induction motor fault detection according to [22].

The contingency of broken bars in induction motors is considered as one of the most important bases of production process breakdown and disruption, representing around 10% of these occurrences [23]. This kind of disruption is more general in large motors that act in heavy load cycles and are exposed to large inactivity, and on account of their increased cost, frequently do not have direct alternatives. In terms of fault monitoring systems, it is as well significant that detection takes place in the initial stages of defect growth when the related damage could be more simply transposed and to let more scope in counteractive interference schedules [24 , 25] presented a reliable indicator for finding out the sternness of non-adjacent BRB in induction motors. [26] dealt with transformative methods for finding BRB faults in induction motors. [23] carried out MCSA in the analysis of induction motor rotors. According to [27], it is pointed out that the MCSA analysis along with vibration-monitoring method could be employed to observe non-invasive sensor signals and categorize the status of broken-bar in induction motors.

Regardless of their minimal cost from the consistency and strength viewpoint, induction motors are likely to fail, as a result of their exposure to various critical environments and improper working conditions or manufacturing faults. Sometimes it is the ageing phenomenon or the poor preventive maintenance which results into the sudden breakdown of the motors. Defects of the bars of squirrel-cage rotors hardly ever cause abrupt failure, particularly in outsized multi-pole motors. Though, if enough amount of rotor bars are damaged, the motor could not start since it could not establish adequate torque. Damage of broken bar takes place in large induction motors that have considerably long beginning time, and the defects should be noticed in the startup time itself. This is greatly significant once the problem like critical unstable magnetic pull and also arcing in the startup of the motor under the defect present. The eccentricity in the air-gap produces fluctuating torque, unstable magnetic flux and lessens the power factor. [28] emphasized that short-circuit faults windings could be diagnosed effectively employing flux monitoring and vibration signals.

The FFT-based technique for example MCSA could not give a tool to identify the defects at some stage in startup. The cause behind is FFT processor is appropriate in static signals and it could not be employed to examine the transitory of the motor wherein both amplitude and occurrence differ. One of the complicatedness presented in the defect detection is the accurate detection of the flaws in induction motor with unreliable load. For example, the FFT-based MCSA technique that employs side-band constituents around basic harmonic to identify the fault, endures this complicatedness. The cause behind is the amplitude of the side-band constituents is load-dependent; consequently, it is potential to diagnose the defect by comparison of the magnitude of the sideband across the basic harmonic in strong and defective motor for the same load in both cases [29].

Finding bearing faults outside the motors by means of the stator current analysis signifies an interesting alternate tool to conventional vibration analysis. Bearing faults cause variations in the stator current spectrum, which could be employed for defect diagnosis purposes. Gearbox bearing faults are considered as one most important reason for such drive-train defects, generally triggered by inadequate lubrication. Several studies, [30 , 31] emphasize that the gearbox bearing is the major source for defects in a drivetrain. MCSA is popularly recognized as one of the condition monitoring techniques for finding and forecasting drivetrain defects [32]. It has been proven lately by [33] that bearing faults in the induction motor influence the stator's current signature and also such inflection is noticeable and analyzable [34].

MCSA, a non-invasive monitoring method, is receptive to the majority of motor faults. In addition MCSA, vibration analysis is as well an efficient monitoring technique in finding a motor bearing and BRB defects [35]. Similar to the conditional monitoring of other types of machines and signal processing are the major parts of the monitoring technique. The method, fundamentally an expansion of the MCSA, is capable of differentiating short-circuited motors from motors which is healthy. Relatively, the vibration technique is most responsive to the finding of bearing faults. The spectral variances between standard and defective bearings at bearing fault occurrences are advanced than those from present and acoustic spectrum. The study by [36] pointed out that the successful identification of induction motor defects is based on the range of appropriate monitoring techniques.

The MCSA is one of the most efficient techniques for the detection and the localization of electrical and mechanical failures, in which the abnormalities become apparent by harmonic components around the supply frequency. Induction motors have a significant role in manufacturing for the rotating machine system on account of their hardihood low expenditures and quasi-absence of repairs. Nonetheless, it arrives that this motor exhibits an electric or mechanical fault due to various reasons. The defects of these machines are diverse in nature and can impact the productivity of the plant. Though the most recurrent is [37] opening or shorting of one or more than that of a stator phase winding, BRB, static or dynamic air-gap abnormalities and bearing defects. [37] used the FFT of the stator current and they examined its phase.

It is exhibited that the fundamentally calculated phase yields better results once the motor works near its minimal load. [38] asserted that MCSA monitoring technique is the most consistent technique of analyzing the inclusive strength of a rotor system. Contrasting to the larger part of techniques, MCSA could yield similar indications without demanding access to the motors.

Bearings have a significant role in the dependability and functioning of all induction motor systems. On account of the close association between motor system development and overall bearing assembly functioning, it is quite complicated to assume the progression of contemporary rotating machines without concern of the extensive application of bearings. Besides, the faults appearing in motors are often associated with the bearing faults. In various circumstances, vibration monitoring techniques are largely employed to find the presence of an initial bearing failure. Vibration monitoring is considered as an effective tool for bearing failures. In general, rolling element bearings includes two rings, which include an inner and an outer ring, amid which a collection of balls revolve in raceways. Contamination and attrition often speed up bearing failures on account of the harsh environments that exist in most manufacturing settings. Despite the defect mechanism, faulty rolling element bearings create mechanical vibrations at the rotating speeds of every part. Mechanical vibration analysis methods are generally employed to observe these frequencies so as to define the status of the bearing. Faulty rolling element bearings generate eccentricity in the air gap with mechanical vibrations. The air gap eccentricities cause vibrations in the air gap flux density that produces visible changes in the stator current [39].

Though BRB does not primarily make an induction motor to stop working, there can be critical secondary consequences. The defective mechanism could give rise to broken parts of the bar hitting the end winding or stator core of a high voltage motor at a high velocity. This could result in serious mechanical impairment to the insulation and a major winding defect might follow, giving rise to an expensive repair and lost production. Contemporary measurement methods along with highly developed computerized data processing and acquisition display advanced ways in the area of rotor bar analysis monitored by the usage of spectral analysis.

The accomplishment of these methods relies on finding by spectrum analysis with particular harmonic constituents produced by faults. [40] stated that one of the most generally employed defect detection techniques is FFT. These techniques largely use the spectral analysis of motor current.

Generally, there are three axis, which include, rotor and stator and symmetry axis and rotor rotation axis in a motor that is consistent with each other in supreme condition. If eccentricity subsists then there is an interruption of any of the axes from the other interruption of all the axes. Eccentricity leads to the uneven air-gap length alongside the stator to rotor circumference. The reasons that produce eccentricity are defined as follows: function of the motors at decisive speed; inappropriate placing of rotor and stator during manufacturing process itself; tendency of mechanical components at critical load; wrong placing of load axis and as well the rotor shaft; ultimately deterioration of ball bearings.

An increased amount of problem is produced on the machine that results in the deterioration of the ball bearings. The ball bearing defect could be due to the inner race or outer race deterioration. The adverse vibrations are created in the stator windings on account of radial magnetic forces produced by eccentricity. The most terrible takes place when eccentricity makes rotor to stator rub that eternally impairs stator core and rotor cage. [41] asserted some undesirable consequences on the characteristics of the motor as a result of eccentricity include, increased power losses on account of poor effectiveness; the temperature of the windings increases; differences in speed and torque will likely to go high. Sometimes, in the axes Petroleum and chemical industry, the failure occurs due to the rise in the temperature of the ball bearing. As per IEEE, it is recommended that, at standard conditions, the temperature should not go beyond 45 degree. The gradual rise in the ball bearing temperature could be due to the deterioration of the inside lubricant. The corrosion and uncleanness of the rotating parts also leads to the reduction of bearing life and eventually failure of the Induction motor. The foremost reasons behind the contamination or corrosion are due to the presence of foreign particles or harsh acidic environment of the industry. Occasionally, the installation problems are also responsible for the gradual failure of the motors.

The classification of induction motor faults is given in figure 1.1. This can broadly be categorized into electrical and mechanical faults and then further into sub-categories.

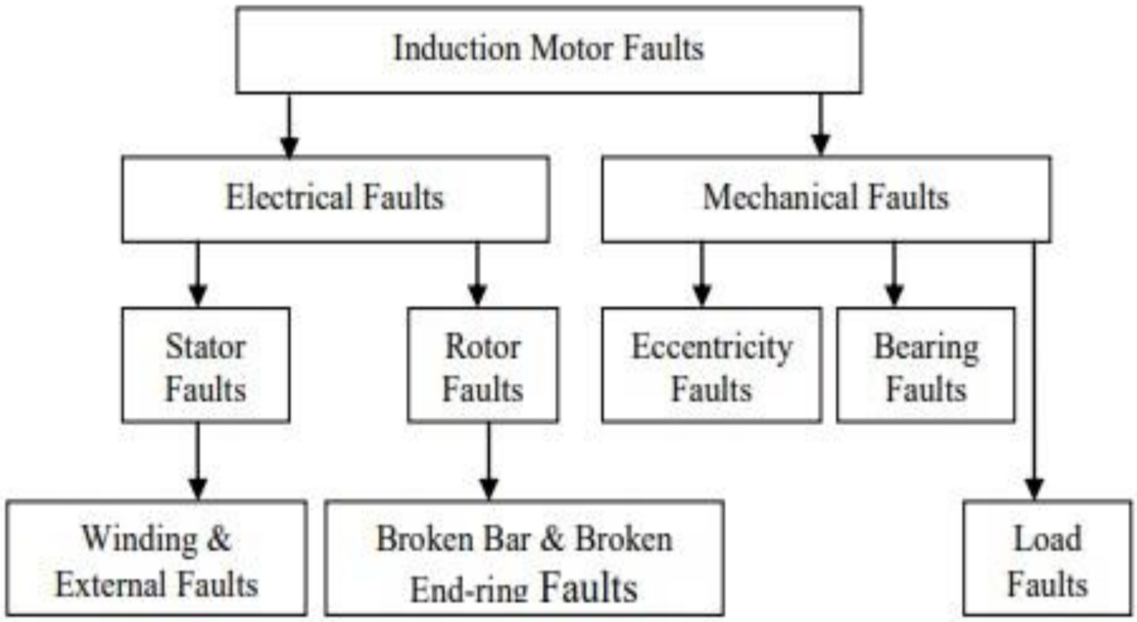

Figure 1.1 Classification of Induction Motor Faults [1]

1.2 Problem statement

Analytic or engine health monitoring systems gained substantial attention over the last decade. Though induction motors are well-known for its reliable and robust functioning because of their uncomplicated design and strong manufacturing technologies, faults do take place and might critically interrupt manufacturing processes and even result in catastrophic accidents. In general, motor faults are associated with core components including stators, rotors, and bearings. Fault location would not just intensify the repair speed, but would as well allow most favorable scheduling of the repair outage. Natural aging processes are also considered as one such factor in induction motors, which are likely to give to various faults. These defects interrupt the protected operation of motors, disturb normal manufacturing, and could lead to considerable cost penalties. The domain of motor condition monitoring identifies those complications, and progressively more relative research is being carried out by industry and academic circles and the current study is one proven example for it. With condition monitoring, an early defect could be identified at an initial stage. If not figured out in time, these defects and slow wear and tear can result in motor disorder and intensification in electricity consumption. The research work adds to the knowledge that initial fault detection of induction motors could not only reduce impairment and energy consumption but as well inhibit the increase of failure or restrict its escalation with regards to severity.

1.3 Objectives of Research

The following are the objectives of proposed research work :

i. To investigate the health monitoring and fault diagnosis of Induction motor
ii. To investigate and analyze the various faults of motor.
iii. To investigate and analyze the various optimization techniques for healthy motor parameter recognition.
iv. To analyze the flux monitoring techniques for Induction motor using experimental setup.

1.4 Significance of the Study

In nearly any activity of humans, it is significant to employ the electric induction motor: from domestic to the most complex manufacturing processes, wherein the conversion between electrical and mechanical energy could not be achievable without this kind of electric machine. The study contributes to prove that the work: accurate health monitoring technique of the induction motor can improve the reliability and can lessen the maintenance costs. It has also been observed from research work that the fault diagnosis in its initial stages in the induction motor is even now considered as a challenging experiment for scholars and academicians. The inherent dependence that presented between electrical motors, the stability of operation at a manufacturing or micro-enterprise level and the economic productivity of every organization have initiated a large number of studies to be performed to establish maintenance methods and particular methods for the monitoring, detection and diagnosis of the different types of faults which could take place in induction motors. The major contribution of the current study is the development of the fault detection capability of various optimization methods.

1.5 Limitations

i. The current study is limited to induction motor only
ii. And the study includes only a few diagnostic techniques, hence accurateness of the diagnostic technique is still indistinct.

1.6 Organization of thesis

Chapter 1 : Introduction

It is the introduction chapter of the proposed study that provides the detailed structure about this research concept "health monitoring techniques and fault diagnosis of induction motors " including the research background, statement of the problem, aims and objectives of the study, research questions, and significance of the study, and as well limitations of the study.

Chapter 2 : Literature Review

This is the review of the literature chapter that explores several works related to the concept of health monitoring techniques and fault diagnosis of induction motors. In addition to these, this study examines in detail various fault detection techniques such as air gap eccentricity, broken rotor bar, bearing fault, etc.

Chapter 3 : Condition monitoring of Induction Motor

It is the Condition Monitoring of Induction Motor chapter. This chapter discusses about the various techniques of condition monitoring used in induction motor.

Condition monitoring is needed to identify, classify and detect various types of failure modes that can exist within a machine system.

Chapter 4 : Experimental study and Performance of Bearing Fault

This discusses the role of health monitoring techniques and fault diagnosis of induction motors. In addition, the chapter deals with fault known as bearing fault and also discussed about the related detection techniques. This also offers about the experimental test bench set to diagnose the effect of bearing fault on the frequency spectrums. The optimization techniques, Particle Swarm Optimization (PSO) and Modified Particle Swarm Optimization (MPSO) has also been presented for bearing fault.

Chapter 5 : Detection and Performance of fault and air gap eccentricity

This discusses the fault known as air gap eccentricity and fault diagnosis techniques that contribute to analyze the defects. Investigation through experimental setup and optimization has also been presented. Various techniques, models and algorithms have been analyzed and the suitability of a particular technique for a specific fault diagnosis has been emphasized.

Chapter 6: Diagnosis and Performance of Broken rotor bar fault

This deals with the motor fault known as broken rotor bar and also discusses with fault diagnostic techniques. Apart from diagnosis through hardware setup, in this chapter the experiments are carried out using two techniques namely Modified Particle Swarm Optimization and Particle Swarm Optimization.

Chapter 7 : Diagnosis and Performance of Abnormal gear teeth fault

It explores the fault known as abnormal gear tooth fault in detail. In addition, the chapter deals with various fault diagnostic techniques in order to propose the better optimization techniques out of PSO and MPSO.

Chapter 8 : Conclusion , Validation and Future Scope

It is the concluding chapter that describes the summary of findings obtained through the discussion section and also provides conclusion to the research topic “health monitoring techniques and fault diagnosis of induction motors” followed by recommendations and suggestions based on the results of the research and thus gives a future scope for the thesis work.

Chapter 2

Literature Review

2.1 Introduction

The section deals with the general characteristics of an induction motor followed by various faults involved in motors. The current chapter presents the literature review on induction motor faults, causes, and various diagnostic techniques. The major topics, including condition/health monitoring techniques and need for diagnostic techniques of induction motor have also been investigated in detail in this chapter. In addition, the major growth in this particular field from extant research to most recent research has been presented.

As stated by [42] the induction motor has largely been used for simple fixed-speed applications and as the author reported it is commonly denoted as the workhorse of manufacturing or engineering field, undertaking a predictable of around 70-80% of electromechanical conversion. An induction motor (IM) is assumed to have equal physical stator as an asynchronous engine, along with diverse rotor construction. In this current study existing categories of electrical motors appropriate for better performance control are presented and comparison has been done with the induction motor. Then the construction and characteristics of induction motors are deeply discussed. The stator of a three-phase induction motor is considered as the static part in line with the repression of a DC motor. The conductors are generally to be found in slits is the covered iron rotor core. If the slits are tilted, better functioning and quieter operation can be achieved.

The work done by [43] dealt with the general description of an induction motor followed by different faults. First, construction of induction motor has been discussed. Then a review of induction motor fault has been presented. Faults like broken rotor bar, mass unbalance, stator faults, single phasing, crawling, bearing faults, etc. are discussed along with causes and effects. An induction motor comprises a magnetic circuit inter connecting two electrical circuits that are to be found on the two major parts of the motors: the stationary part known as the stator and the rotor which is considered as the rotating part of motor. While the stator winding of an induction motor is connected to a three-phase supply, a uniform revolving magnetic field is produced within, which provokes electromagnetic in the rotor that is free to rotate concentrically with the stator core by means of ball bearings.

2.2 Induction motor- Faults and Diagnosis

The research work done by [44] dealt with various fault diagnosis of three-phase induction motors. The study also addresses the application of motor current spectral analysis (MCSA) for the detection of uneven electrical and mechanical states that indicate or might lead to, a failure of induction motors. In addition, the study differentiates between the "fault signals" of the following faults: eccentricities and broken bars (BRB) in such induction motors. The study presents a real-time execution of an online protection system for fault detection and diagnostic techniques of induction motor. The system could detect the online presence of a number of defects such as broken bar of induction motor, bearing faults in addition to stator turn to turn short. The study also intended to accomplish the operational efficiency level accomplished by the original design, or, if feasible, a larger than the design-efficiency level in the induction motors with two projected approaches: qualitative assurance approach and analysis approach.

Accordingly, it is [45] pointed out that it can be possible to detect faults and defects of the motor's actual condition with continuous monitoring, and it is also possible to avoid expensive, unanticipated shutdowns of production methods, with financial losses well further than the expense of the motor itself. In order to reduce motor-related problems, assisting the maintenance employees in their decision-making process, and making the appropriate application of fault diagnosis systems, professional systems derived from neural networks have also been presented for automatic fault diagnosis. Though, all these techniques, to the best of author's knowledge, act under steady-state forms and are not appropriate in a temporary method. In order to resolve this problem, the current paper deals with an automatic system for developing optimized diagnostic techniques for fault identification when the machine operates in transient conditions. The given technique is first theoretically presented, which is later applied to the experiential diagnosis of broken bars in an induction motor.

It is proposed by [46] that a novel technique particularly for fault diagnosis of induction motors and stated that the diagnosis of induction machines using Fourier transform relies on tracking the frequency signature of each type of fault in the current's spectrum, but this signature depends on the machine's slip and as well the supply frequency, consequently it should be recalculated for every working condition by expert or by diagnostic techniques. In addition, sampling the current at increased rates in long times are required to accomplish a better spectral solution that actually demands huge memory space to collect and deal with the current spectra. So, the current study proposed a technique to resolve both problems. The tracking analysis of the defect elements employing the harmonic order as individual variable rather than the frequency creates a novel fault signature that is the same for any operating condition. In addition, this signature can be concentrated in just a very small set of values, the amplitudes of the components with integer harmonic order. This new approach is presented hypothetically and later authenticated experientially.

The fault diagnosis of induction gained considerable attention, as a result of their reliability and capability to implement an extensive range of induction motor’s working conditions [47]. These techniques calculate the time-frequency (TF) division of the stator current, wherein the systems of the related defect elements could be detected. Also, a considerable amount of studies in this field have largely intended to improve the resolution of the TF divisions, facilitating a better difference and detection of fault harmonic elements. Nonetheless, since the resolution enhances, computational requirements largely increase, limiting its execution in low-cost devices for carrying out on-line fault diagnosis. In order to deal with these drawbacks, the application of the Short-frequency Fourier transform (SFFT) for fault detection of induction motors working within transient techniques is proposed. The SFFT not just holds the resolution of traditional methods, for example the short-time Fourier transform, however as well accomplishes a radical decline of computing time and memory sources, making this application more appropriate for on-line fault diagnosis.

The effort pointed out that the application of efficient signal processing tools (SPTs) to get proper indices for fault detection in induction motors is the essential component of every fault detection procedure. In the early part of the current study [48], the author emphases on Fourier-based techniques, such as fast and short-time Fourier transform. Also, all used SPTs that have been applied for fault identification in IMs are examined in depth. Then, their competency and their difficulties to obtain indices in transient and stable state forms are evaluated from various aspects. Numerous types of faults, such as, eccentricity, broken rotor bar (BRB), and bearing faults as the most important internal defects in induction motors, are examined. Fourier processor as the most appropriate processor for various defects has limitations and benefits. Its most significant limitation is in the managing of transient signals. In conclusion, in order to overcome this drawback, using a wavelet processor has been recommended.

It is reviewed by [49] , motor current signature analysis (MCSA) for fault diagnosis of induction motor. MCSA has been investigated for BRB and end-ring faults identification in an induction motor. And the paper has examined the induction motor fault diagnosis techniques by means of a stator currents processing. Mechanical faults identification on the basis of stator currents has been investigated in detail. In general, bearings defects have been classified as distributed or local. Failures are generally taking place as a result of various causes that are linked with the design, production or application processes. These faults could have as effects: magnetic field distortion, risk of electric and stator damages, overheating phenomena, abnormal currents, noise and problem of additional torque. An appropriate choice of signal processing methods for fault identification for various induction motor working conditions is considered as a major issue.

As pointed out by [50] induction motors are largely employed motor for different industrial applications as they are strong, uncomplicated in structure, and effective. Conversely, induction motors are likely to various defects in their lifetime on account of hostile environments. If the defect is not identified in its initial stage, it might result in an unanticipated shut down of the whole system and huge loss in firms. Hence, it is obvious that scope of this motor is extreme to a large extent. The current work provides identification of both internal and external faults of induction motor. S-

Transformation, which is advanced than STFT since it does not include any cross conditions, is employed for bearing fault identification, and random forest, an algorithm that is simple to execute and demands lowest memory, is employed for identification of external faults. The fault could be identified with more accurateness in premature state results in enhancing the consistency of the system.

The research work by [51] presents a technique known as supervised sparsity-based wavelet feature (SSWF) for the identification of bearing fault that includes wavelet transform and sparse coding. SSWF has been extracted from vibration signals with various steps: develop a wavelet transform with the fault-related wavelet transform coefficients; design a structured dictionary that combines the signal characteristics and class information; employ the dictionary to execute the sparse coding of the wavelet transform vectors that could be resolved by basis pursuit (BP) and finally compute the SSWF from the sparse coefficients. Sparse coding derived from a structured dictionary could detect a strong representation of the signal and simultaneously, include the class information. Consequently, SSWF is capable of firmly and discriminatively replicate various fault categories that specify it's prospective in bearing fault diagnosis. Tests on two bearing cases are carried out to prove the benefits of SSWF in the identification of bearing faults.

One of the most important considerations for induction motors is their speed control. In general, proportional-integrator controllers are employed as a speed regulator. Regulating the gain of proportional-integrator controller is considered time-consuming that actually demands systematic considerations [52]. For this reason, the study suggested that fuzzy controllers are assumed to effectively deal with such problems.

In this study, at first, drive of a three-phase induction motor has been constructed on the basis of PI controller and later fuzzy logic controller is executed. This study deals with a speed control technique on the basis of so-called fuzzy logic for drive of an induction motor. The inputs taken up in the study are speed error whereas the output is speed. To conclude comparison analysis has been done between the proportional-integrator and fuzzy controllers that exhibits dominance of the fuzzy controller over proportional-integrator controller.

The work by [53] is completely on the basis of novel speed control system with the use of fuzzy inference logic on an induction motor. The model of fuzzy logic is considered remarkable as it eradicates complex hardware installation of factory modeling. Fuzzy control as well as authenticates nonlinear design methods employed in induction motor control. The current paper explored the consequences of rotor resistance power on the speed of an induction motor by carrying out the proposed experimentation in the laboratory. Afterward, fuzzy logic controller has been used to a similar experiment in order to instruct the system to calculate the output, that is, speed of motor, when distinctive input parameters are transformed consequently. The induction motor state is diagnosed employing a pattern rule of fuzzy inference logic. The preliminary findings exhibit that the said fuzzy approach could be effectively employed for precise stator fault diagnosis.

This is also examined by [54], about the various fault diagnosis that can be used for induction motors. The underlying principle of this study is to develop a novel technique to find and categorize mixed and individual defect in an induction motor. The conditional monitoring and fault analysis of induction motors have fortified in recent periods from traditional techniques to artificial intelligence (AI) techniques. These techniques don't generally demand expertise of motor parameters or any paradigm of the system necessitated MCSA is conventional non-invasive technique that uses the spectral analysis of stator current for fault diagnosis. However, the drawback of MCSA is that the magnitudes of characteristic elements are depending on the load difference that becomes complicated for defect diagnosis in the motor. A fuzzy logic approach may help to contribute to detect induction motor faults. In fact, fuzzy logic is indicative of individual thinking processes enabling decisions to be made based on uncertain information.

It is articulated by [55] that artificial intelligence technique are also practical to induction motors in order to find faults and diagnosis. The status of the motor is defined by employing linguistic variables. A knowledge base, including rule and database, is established to deal with the fuzzy inference. The conditions of induction motor have been diagnosed with a compositional regime of artificial intelligence methods. The successful finding of induction motor faults relies on the range of appropriate techniques taken up. The study emphasized that artificial intelligence is considered as a unfailing choice since there is no common and accurate analytical model that describes successfully the induction motor within defect conditions. The underlying principle of this study is to propose an online system able to detect the stator form of the induction motor by observing the motor currents. All through this study, artificial intelligence technology is used to evaluate the information and make decisions and concluded that the technique has the potential to find the motor condition with increased accurateness.

According to [56] stator winding faults, for example, the inter-turn short circuit is considered as the most recurrent source of defects in induction motors. Early identification of this fault and place of the faulty stage at various loads would eradicate certain consequent defect to adjacent coils and stator core, lessening then the maintenance cost. To accomplish this objective, the current study deals with a new technique of diagnosis and finding of this particular inter-turn short circuit fault applying wavelet transform and neural networks (NN). This technique includes assessing the stator current by wavelet transform so as to calculate the energy-related to the stator defect in the frequency bandwidth. Later, this energy is employed as input for a neural network classifier. The findings acquired are remarkable and the technique is capable of detecting any least number of shorted turns and the defective stage even within various loads of the machine.

Table 2.1 Induction motor- Faults and diagnosis techniques

S.No	Author	Year	Approach	Findings
1	Janrao and Ambekar [57]	2018	Signal processing technique	• Signal processing used for fault detection • These techniques are easy and economical to implement. • The author concluded that these techniques are well suitable for online health monitoring system for induction motors.
2	Bhattacharyya , *et al*[58]	2015	MCSA	• MCSA is wide spread method for analyzing induction motor faults. • Online monitoring could be done efficiently by this technique, which further reduces the risk of defect and damage.
3	Kathiravan and Prakasam [59]	2014	MCSA	• Common faults like Cracked or BRB are easily detectable through MCSA. • It also contributes to the fault detection on account of significant noise and the line current.
4	Hamdani et al [60]	2011	Neural network	• Neural network is largely used for external faults detection. • Neural network has the capability of oversimplification and for this purpose, the inputs should be correctly standardized.
5	Jose and Jose [61]	2013	Fuzzy logic inference	• In fuzzy logic, the fault status of the induction motor is defined employing linguistic variables. • It also concludes that a imbalance current from source might be considered as faulty condition which could be resolved by observing the voltage and creating new regulations in the fuzzy inference system.
6	Mohamed et al [62]	2015	Wavelet transform	• The wavelet packet transforms as an appropriate technique for identification of defect in three-phase induction motor. • It also contributes that fuzzy logic can be employed for mixed eccentricity defect identification.

S.No	Author	Year	Approach	Findings
7	Marcelo et al [63]	2012	The FFT (Fast Fourier Transform)	• FFT largely used for on-line fault detection of induction motors at initial stage. • The status of the machine is determined by examining the frequencies separately during motor operation.
8	Mohammadi and Akhavan [64]	2014	Parameter Estimation Algorithm	• The benefit of this estimation technique integrates significant freedom in the range of measured signals. • The method is believed to provide enhanced results closer to actual values than the standard experiments.

2.2.1 Broken rotor bar (BRB)

The Broken rotor bar is one of the largest occurred induction motor defects which might result in major motor fault to the motor if not identified timely [65]. Earlier efforts on BRB diagnosis have been concentrated on current signature analysis employing wavelet transform. These techniques demand precise slip estimation to locate fault-related occurrence. The current study investigates a new method to BRB diagnosis without slip estimation, on the basis of the Hilbert transform. Numerical and experiential researches have verified that the proposed technique of the current study is efficient in diagnosing BRB defects for enhanced induction motor condition monitoring and defect review.

Early fault identification is extremely essential to lessen the maintenance expenses and prevent increased cost and impulsive downtimes. The underlying principle of this paper is to propose an efficient and responsive technique for fault identification in low load conditions. The defects intensity is considered as one, two, and three BRB [66]. The results have approved that the projected method is efficient for diagnosing rotor bar breakage defect in motor and classification of fault strictness. The proposed technique is capable of present a sub-band which entails the fault features and proven that the technique is simple, economical, dependable, and accurate.

The work [67] presents a method for the detection of broken rotor bars (BRB) in an induction motor. After introducing a simplified dynamic model of an induction motor with broken cage bars in a rotor field reference frame which allows for observation of its internal states, a fault detection algorithm is proposed. Two different motor estimation models are used, and the difference between their rotor flux angles is extracted. A particular frequency component in this signal appears only in the case of broken rotor bars. Consequently, the proposed algorithm is robust enough to load oscillations and/or machine temperature change, and also indicates the fault severity. The method has been verified at different operating points by optimizations and also experientially. The fault detection is consistent even in times, wherein traditional techniques provide vague findings and results.

It is also expressed by [68] that that the FFT technique is effectively employed for the BRB fault identification function in the induction motors. It is on the basis of the common-steady condition analysis of the induction motor. This technique is effectively employed with the MCSA technique for last thirty years. On the other hand, this technique is endured with some critical drawbacks for example; it is appropriate just in the consistent load setting not for the variable load. In light-load condition, it is quite complicated to differentiate among healthy and defective rotors since the qualities of BRB fault frequencies are very near to basic module and their amplitude is comparatively small. Accordingly, identification of the defect and categorization of the fault severity in light load is almost impracticable. To deal with the above complications of the FFT based method has been presented.

As articulated by [69] it is true that substantial attention has been shown for induction motor fault diagnostic techniques predominantly for the BRB fault. This defect type comprises around 10% of the total cage rotor induction machine defects. Derived from three phase time domain model, the rotor broken bars with many settings have been simulated to inspect the noteworthy torque speed quality in every condition. The proposed fault diagnostic technique is able to identify the kind of the BRB faults in the squirrel cage induction motors. The proposed system is proven to identify the number of rotor broken bars. Besides, it is sufficient for application in an on-line fault diagnosis technique in induction machine drive.

Table 2.2 Broken rotor bar (BRB)

S.No	Author	Year	Approach	Findings
1	Powers [70]	2015	BRB	• BRBs results in critical damages to motor if not fixed at early stage. • Wavelet analysis of the startup transitory currents enhances the consistency of finding BRBs wherein the axial air channels impact the current spectra.
2	Zhao et al [71]	2015		• A novel fault diagnostic technique for BRB in the induction motor of hoister, on the basis of multifractal (MF) dimension is introduced. • To conclude, MF is proven to extract the defect of BRB and have a better detection result.
3	Filho, *et al*[72]	2018		• For the diagnosis of BRB in both low and high slip conditions, stator current analysis is done by wavelet transform. • The Computer simulations define the better performance of the proposed technique and are proven to be simple and easy to execute.
4	Cekic and Eren [73]	2017		• The frequency band size analysed through Wavelet transform includes all fault induced frequencies on account of rotor speed differences. • The RMS value for BRB fault-related frequency band is corresponding to the baseline data to find any BRB defects.

2.2.2. Bearing fault

The research work carried by [74], investigated both regular bearings and bearings with external and internal defects. The constraint point of the determination of the intensity number is also presented. Besides, the study looks for informations about the basic defect signal on the energy stored in each level of decomposition.Wavelet transform has the ability to allocate concurrent time-frequency analysis, subsequently it is the right tool for examining transitory occurrence and non-stationary signals. The technique of MCSA has been used many decades ago; on the contrary the FFT technique has certain drawbacks in some conditions once the speed and the load torque are not persistent. The FFT has issues on account of a non-stationary signal if it is must to report precisely the frequency characteristics of the faults. The findings acquired are considered remarkable which certainly could be employed to diagnose the bearing faults of motors.

The efforts by [75] presents a description of bearing faults, stator and rotor fault analysis methods of an induction motor. And, the existing methods employ acoustic signals. Different situations of the single-phase induction motor have been investigated: healthy motor, motor with BRB and faulty ring of squirrel-cage, motor with bearing faults. Categorization has been carried out employing the nearest neighbor classifier. The proposed methods have revealed improved effects for investigation of faults such as bearing, stator, and rotor of the induction motor. The proposed method could find applications for fault investigation of other kinds of rotating motors.

The research work in [76] investigates different fault diagnostic techniques and detection employing artificial networks. In this paper, analysis has been carried out on induction motor, since this motor is broadly employed in industries on account of their strength, uncomplicated maintenance, etc. The current responses of a faultless motor, motor with bearing and faults such as rotor and stator has been examined. The feature extraction method is carried out in time domain only. From the results of the study it is evident that amongst diverse transfer functions in neural network the “trainlm” acts finest however “traingdm” executes not well for fault finding for bearing, rotor and stator faults.

As specified by [77] bearing problems are considered as one of the most important causes of induction motor defects and it has a significant role in the dependability and functioning of all motor systems. Besides, the majority of the defects taking place in electric motors are frequently associated with bearing faults. Various techniques are employed in fault diagnosis on the basis of the stator current analysis by using signal processing techniques. The current study has used the periodogram technique, but the technique is considered having several drawbacks. To resolve this issue, a new technique on the basis of the auto-regressive modeling of the stator current is employed in this study, therefore enhancing the frequency resolution to the detriment of significant computation time. Accordingly, two improvements are developed to lessen the computation time whilst giving enhanced readability of the stator current scale with the utilization of the proposed method.

Bearing faults are one of the major single sources of motor defects. Neural Networks and other decision support techniques are broadly employed for early identification of bearing faults [78]. The conventional decision support techniques actually demand feature extraction and categorization as two different stages. In this study, the application of Neural Networks is developed for a fast and precise bearing fault identification system. The feature extraction and categorization stages of the bearing fault identification are intermixed into a single learning body with the execution of a neural network. Execution of neural network results in more effective systems with regards to computational difficulty. The categorization performance of the presented system with actual bearing data exhibits that the lessened computational complication is accomplished without negotiation in defect detection precision.

Table2.3 Bearing fault

S.No	Author	Year	Approach	Findings
1	Glowacz, *et al [79]*	2017	Bearing fault	• The author emphasized early fault diagnosis particularly for bearing fault. • The proposed method could be employed for analysis of the single-phase induction motors, and for other rotating electrical motors.
2	Boudinar, *et al [80]*	2016		• The author highlighted that huge financial losses can be avoided by premature detection of bearing faults. • The work also concludes the dependability of the initial bearing fault identification on root multiple (RM) technique.
3	Singhal and Khandeka [81]	2013		• The study concludes that extreme load, increase of temperature within the bearing results in bearing faults. • The different defects in bearing could be categorized as per the affected element: outer and inner raceway effect, ball defect.
4	Kripakaran and Reddy [82]	2017		• The work described that dirt, and extreme heating causes the lubricant to stop working that enhances failure process. • With the finite element technique, the motor is designed to analyze bearing faults in induction motor.

2.2.3 Air gap eccentricity

As expressed by [83] motor faults are largely affected by many factors and air-gap eccentricity is one such fault which considerably received lots of attention. There are two kinds of air-gap eccentricities, which include static and dynamic air-gap eccentricity. Eccentricity is referred to as the state of uneven air gap which subsists between the stator and rotor. In terms of static air-gap eccentricity, the locate point of the least radial air-gap length is preset in space. Both categories of eccentricities create extreme stressing of the motor and intensely raise bearing corrosion. One of the causes for non-uniform air-gap of a motor is as a result of manufacturing defects. Also, the study emphasized some other causes of eccentricity, which include bearing wear or resonance at significant speeds, and so on. Multi-resolution wavelet analysis (MRWA) has been applied to rot the higher level frequency components of flux intensity and current of the motor with distinct levels of eccentricity. The findings of the study exhibit MRWA will be a better alternative to FFT in finding air-gap eccentricity in induction motors.

The research work carried by [84] investigated the causes behind air gap eccentricity faults. Air-gap eccentricity might be noticed by finding the features current signature pattern being suggestive of irregular levels of air-gap eccentricity and to later that signature. Air-gap eccentricity in electrical machines can occur as static or dynamic eccentricity. The effects of air-gap eccentricity produce unique spectral patterns and can be identified in the current spectrum. The analysis is based on the rotating wave approach whereby the magnetic flux waves in the air-gap are taken as the product of permeance and magnetomotive force (MMF) waves. The diagnosis is on the basis of the rotating wave technique by which the magnetic flux bearing in the air-gap are obtained as the product of magneto-motive force (MMF) waves. The topic of on-line identification of air-gap eccentricity in induction motor is as well investigated in this study. Air gap eccentricity produces a ripple torque that further results in speed pulsations, vibrations, acoustic noise, and even an abrasion between the stator and rotor. Therefore, it is critical to detect air gap eccentricity as early as feasible.

The work by [85] looks at eccentricity fault identification for a speed induction motor. Eccentricity fault is literally associated with internal defects of the motor; it seems when there is an asymmetrical air gap between rotor and stator. The paper chooses to analyze mixed eccentricity fault (i.e., both mixed of rotor and stator). Though the induction motor is well recognized to be strong, it is likely to certain limitations on account of functioning conditions. Therefore, identification of faults intrinsic to the motor is critical for increasing reliability, security and preventing unnecessary or even terrible failures. The study proposes to employ the Wavelet Transform DWT with distinctive techniques for the diagnosis of motors to identify faults and as well their intensity. The acquired findings have exhibited that the proposed techniques could efficiently diagnose and find mixed eccentricity faults.

It is also proposed that an online fault diagnostic technique that is on the basis of assessments of internal main air gap density of a motor and with an array of Hall Effect flux sensors [86] is very practical. Such instrumentation is rationalized for large specific induction motors with specifically high-reliability necessities. Basic theory behind the air gap intensity as a function of time and as well space, in addition to its falsifications introduced by a number of defects, is investigated in this study. Based on this system, this study recommends an inclusive condition monitoring technique to analyze induction motor defects such as stator turn-to-turn shorts, rotor and static and dynamic eccentricity that might be present separately or concurrently. The principles put forward in this study are demonstrated by general optimizations and are experientially confirmed on an online condition monitoring system model.

As a matter of fact, expressed by [87] that the identification of early eccentricity faults in motors is one of the major intentions in the maintenance of manufacturing/engineering systems. Even in new motors eccentricity generally takes place on account of the increase of tolerances in manufacturing stage. In general, MCSA detect an increased levels of both eccentricity types, such as static and dynamic eccentricity, however it is extremely hard to find such defects if they seem independently and the defect signatures are occurred in stator current spectrum on condition that the two types of eccentricity subsist together and it is not quite simple to differentiate them. The current study intends to diagnose low levels of purely static eccentricity (SE) in motor employing time stepping finite elements (TSFE) technique, short portrayal of this method modeling will be exhibited in first section of paper. The use of flux signature analysis (FSA) to find purely SE in motor for stable and non-linear permeability is integrated in the next section of study.

Table2.4 Air gap eccentricity

S.No	Author	Year	Approach	Finding
1	Reddy and Kumar [88]	2019	Air-gap eccentricity	• An air-gap eccentricity fault might be as a result of the mechanical issues or due to abnormal electric or magnetic system. • The proposed technique by the study obtains the differential flow of a stator winding of induction motor as input, instinctively finds the defect type and its complications.
2	Yahia, *et al*[89]	2016		• The study proposed an effective time-domain technique on the basis of Prony's method for the air-gap eccentricity fault detection in motors to deal with the discrete fourier transform problems (DFT). • The proposed technique helps tracking the frequency of the air-gap eccentricity defect distinctive element with an increased accuracy employing only a small amount of data samples.
3	Ojaghi, *et al [90]*	2016		• For the static, dynamic and mixed eccentricities in induction motor faults, author proposes a model-based fault diagnosis method. • An algorithm is presented for the eccentricity fault management .
4	Sousa, *et al [91]*	2016		• A brief review on causes and consequences of three eccentricity fault is done for induction motors. • The outcome obtained in this study is believed to define some of three phase induction motor parameters, such as motor power supply at its vibration signal.

2.3 Faults: Causes and Effects

This is the study [92] of the effects of various faults on induction motors. These motors are largely to be found in various applications. However, these motors are likely to get affected by various internal and external pressures that give rise to various kinds of faults. The manufacturers and also the users of the motor drives are literally caring about the consistency of the drives while used in an application. Consequently, it has become particularly significant that any defects taking place in these motors must be identified at initial stage itself. Therefore, for the detection it is essential to examine the effect and causes of these faults on the functioning of motor. In this study a 5HP induction motor has been simulated in MATLAB and the causes of different types of switching faults have been examined. The switching faults for example rectifier diode faults and inverter IGBT fault have been simulated employing a roller switch and turn on and turn off has been done at 0.5 sec. The findings noticed that all these defects could ultimately influence the motor performance and the most critical fault amongst these is the defect on the IGBT switches.

It is evident from [93] which focuses on the causes and effects of different motor faults and also development of diagnosis methods for these faults. Major categorization of switching faults are the defects taking place in the rectifier part, defects taking place on the DC link capacitor, defects taking place on the inverter side. The study deals with the causes and effects of various faults appeared in a motor system. The most common defects in motor are classified as rotor, bearing eccentricity and stator faults. The mainstream of all rotor defects are caused by blend of different stresses such as residual, dynamic, thermal and environmental. Air gap eccentricity is likely to cause noise and vibration issues. External materials, which could cause block the ventilation paths, might comprise a stress, as could moisture that would harm and fail the basic rotor components.

As articulated in the work [94], which explores detection of faults and causes in induction motor. This research presents an outstanding health monitoring for motor systems to identify the intensity level of mechanical defect conditions. The main contribution of this study is to find the precise location of the defect incidences in the rotor.

The causes of faults are generally classified in to two groups, mechanical and electrical: mechanical causes of failure include mechanical unbalance, bearing fatigue, overheating, and loss of cooling, etc, whereas electrical Causes of failure include poor power quality, insulation faults, resistance unbalance, etc. prolonged starting, loss of supply voltage are also some of the causes of failures.

Table 2.5 Faults: Causes and effects

S. No	**Author**	**Year**	**Findings**
1	Patole and Bhagwat [95]	2016	Winding faults, which largely take place in the higher level induction motors as a result of increased voltages used, the rotor defects in all the motors owing to extreme slow destruction of the motor or caused by bearing and manufacturing defects.
2	Fireteanu [96]	2013	High vibration and temperature, abnormal voltage and chemicals, overheating and electrical faults are generally associated with insulation failure.
3	Bazurto, *et al*[97]	2016	The author presents an analysis of the causes of the most common defects in induction motors. Intrinsic weakness of components, structure and manufacturing. The slow decline due to wear and tear, fatigue by pressure or deterioration. Wrong assembly, voltage imbalance, pollution and temperature are also some of the other major causes.
4	Alwan and Sabbagh [98]	2017	Worsening of the winding insulation generally starts as an inter-turn defect entailing some turns of the wind speed. A turn defect in the stator winding of a motor results in a greater rotating current to flow in the shorted turns.

2.4 Various condition/health monitoring techniques and its need

It is pointed out that these days the use of health monitoring of motors are increasing because of its potential to lessen operating costs, improve the consistency of function and enhance service to users. Condition Monitoring particularly of induction motor is considered as a fast developing technology for online detection of faults at early stage itself. This article integrates an inclusive review of various kinds of faults take place in induction motor and as well draw attention to the most recent trends in condition monitoring technology [99]. This paper includes the various monitoring techniques of three phase induction motors that are employed formerly and as well significant for these days like artificial intelligence based identification methods and as well as thermal monitoring, air gap torque monitoring, noise and vibration monitoring and MCSA.

According to [100] condition based monitoring of induction motor in industrial related applications is largely rooted in various parameters monitoring. In line with the sensor measurement used, the majority of techniques for induction motor monitoring can be categorized into various categories, which include vibration monitoring, temperature monitoring, acoustic emission monitoring, current/power monitoring, etc.

The study by [101] determines health condition monitoring of induction motors. A technique known as spectrum synch is taken in this study for incipient motor defect detection employing electrical signals; fault identification in this study will emphasize faults bearings and rotor bars that together represent more than half of motor defects. A central kurtosis indicator is developed to extort descriptive features from the defect information spectrum and establish a defect index for early induction motor fault diagnosis. The efficiency of the proposed spectrum synch method is tested on induction motors with BRB and with impaired bearings. The central kurtosis is recommended to create fault indices for induction motor condition monitoring. Test findings have exhibited that the developed spectrum synch technique and also central kurtosis indicator has the potential to capture motor defect characteristics efficiently and could present more precise induction motor health monitoring information.

As articulated by [102] that automatic condition monitoring is considered necessary to detect faults of induction motors. There are different techniques to define motor defects and analyze them. These algorithms could be categorized into different domains such as time, frequency, higher order spectral analysis, NN, etc. Various condition monitoring techniques, for example, testing of current spectrum, vibration and thermal monitoring have been developed for different kinds of faults in induction motors. The review of the existing health monitoring and maintenance techniques are presented in the paper. The protection techniques are focusing on the following fields: thermal protection, stator insulation monitoring and defect identification such as, bearing, BRB, and air-gap eccentricity detection.

As pointed out by [103] machine condition monitoring is receiving considerable significance on account of the need to intensify reliability and to lessen the probability of production loss owing to machine breakdown. By evaluating the signals of a motor functioning in normal and defective conditions, identification of defects including mass unbalance, shaft misalignment, gear failures, and bearing faults is feasible. These signals could as well be employed to identify the initial defects of the machine constituents, by means of the online monitoring system, lessening the likelihood of terrible damage and the downtime. Artificial intelligence methods like neural network could be executed in the system for automatic detection and analysis of motor conditions.

The study by [104] developed a health monitoring system that integrates operating condition monitoring (OCM) and as well fault diagnosis analysis (FDA). The OCM in the study employs a vibration identification approach whereas FDA employs a vibration-electrical approach on the basis of different indices. The system could obtain real-time electrical signals. When a deviant vibration has been noticed by employing OCM, the FDA can be used to categorize the kind of faults. The findings point out that the OCM could effectively diagnose induction motors’ healthy status, and FDA could categorize the different damages such as stator and rotor fault, bearing and eccentricity fault. The FDA with the hybrid approach is considered increasingly consistent than the conventional approach employing electrical identification alone. The proposed condition monitoring system in the study is believed to provide uncomplicated and accurate maintenance information to enhance the consistency of motor operations.

Table 2.6 Condition/health monitoring techniques and its need

S.No	Author	Year	Approach	Findings
1	Duan and Zivanovic [105]	2014	Sparse grid optimization method	• The author develops a novel technique for effective and precise monitoring of the stator winding fault. • Sparse grid optimization technique used in the least squares analysis of the circuit parameters which categorize the condition of a developing fault.
2	Tsypkin [106]	2017	Vibration analysis	• The findings emphasized that Vibration analysis can be one of the most effective techniques employed for health monitoring of rotating machines. • On-line condition monitoring of the motors has been employed for the detection of faults by the author.
3	Tsypkin [107]	2013	Vibration analysis- a twice line frequency component	• Vibration analysis as a condition monitoring technique of induction motors is effective method for diagnosing various faults in motors. • The study is based on the ability to evaluate vibration data.
4	Hurtado, *et al [108]*	2015	Tagging-compounds	• The author emphasized the use of special tagging compounds known as “smoke detectors” for monitoring of induction motors.

2.5 Research gap

The current work delves into number of faults and diagnostic techniques of induction motor. The previous work done in the area of condition monitoring had explored many detection techniques like:

i. It was explored by [45,45] that various fault diagnosis of three phase induction motors in order to prevent financial loss for the firms and manufacturing units.

ii. The research work by [55] employs artificial intelligence technique to motors to find faults and diagnosis however [57] put forward that signal processing technique can be considered as fault detection technique whereas [59] suggested MCSA as advantageous technique for fault detection.

iii. In the work carried by [65,67], technique for detecting BRB faults was developed however on the other side [74] and [77] investigated bearing faults.

The all literature studies specifies that for health monitoring and fault diagnosis of electric machines, various techniques such as thermal monitoring, noise monitoring, vibration monitoring and flux monitoring are frequently used. All these techniques require special purpose sensors and other condition monitoring devices to be installed for the health monitoring. Many of them requires a costly setup to integrate and diagnose the early failure of the induction motors. It has a widely acknowledged requirement that a diagnostic technique should be noninvasive and must be able to investigate the faults precisely at a least cost.

The prominent gaps observed through intensive literature review are observed as following:

a. Previous research on health monitoring of Induction motor through Magnetic field analysis demand costly setup and were limited to identify few faults. Therefore, there is a need to explore a low cost solution for the diagnosis of various faults of induction motor.

b. Very few experimental studies have been available which could diagnose the single fault in induction motor with the different signal processing techniques. Hence, there is a need of one of more blend methods that could consistently diagnose the failure of induction motor at an early stage.

c. The research work does not only diagnose faults but explore the need of low cost optimization techniques for mentioned motor in particular by considering magnetic flux as primary fitness function, in which the previous mentioned studies seem lagging.

2.6 Summary

The chapter included important characteristics and function of induction motor. In addition, the chapter dealt with various faults and techniques for clear understanding of induction motor and also to help firms to avoid unnecessary financial losses. As it is not only enough to investigate motors alone, the chapter also included various diagnostic techniques and need of condition monitoring techniques. The review of different fault diagnostic techniques for induction motor presented in this chapter specifies that the earlier proposed methods still require further exploration. The section also includes a comprehensive review of different types of faults occur in induction motor and also point out the latest trends in condition monitoring technology.

Chapter 3

Condition Monitoring of Induction Motor

3.1 Introduction

The condition monitoring of IM is the regular performance assessment and machine health throughput is helpful operating life and identifying faults at their inception. By condition monitoring the induction motor parameters are monitored on the whole when it is performing on its complete capacity of load through techniques of effective measurement so that the life of motor and its effectiveness rises. In condition monitoring there are two major components, one is the detection of fault through some effective and comprehensive techniques and the second one is the steps to decrease the impact which reduced the induction motor efficiency since the already existing error cannot be removed to 100 percent extent. Condition monitoring has huge importance due to the following reasons namely: 1) improved efficiency of operation; 2) increase reliability and availability of machine; 3) reduce the costs of maintenance; 4) improves management of risk, improved security, reduced inventories of spare parts, improved machine condition knowledge, expanded life of machine operation, improved relations of customer, removal of chronic failures, decrease of post overhead failures to find the faults associated to various parameters which offers a brief problem analysis.

The condition monitoring is a noninvasive measurement technique that is the measurement is made outside the induction motor. The condition monitoring is helpful in many sectors where the induction motor is installed frequently in large number. This chapter discusses about the various techniques of condition monitoring used in induction motor. Condition monitoring is required to detect, identify and then classify different kinds of failure modes that can occur within a machine system. Often several different kinds of sensors are employed at different positions to acquire vital signals from the machine. These signals are examined and features are retrieved to acquire data of various machine faults and mainly the machine health.

3.2 Techniques of condition monitoring for Induction Motor

Induction motor is used mostly in industrial applications because of its economical, technical and favorable reasons [109]. It has been observed that during the drive system operation the induction motor faces various kinds of abnormal conditions which in turn create different kinds of failures and faults in machine thereby influencing the system of production. Hence to avoid such faults of induction motors various condition monitoring techniques are used for the health diagnosis of motor. By using these conditions monitoring techniques the induction motor can be hindered from different failures which in turn enhance the production and efficiency. Several techniques of condition monitoring have been discussed below briefly.

3.2.1 Thermal Monitoring

The electrical machines thermal monitoring can be finished by estimating the local temperature of the motor or by the assessment of parameter [110]. Due to small turns in stator winding the stator current value will be greater and hence it generates huge amount of heat if appropriate precautions must be considered and results into motor destruction. This model is categorized into two major parts namely Model based on lumped parameter and model based on FEA (Finite Element Analysis). Finite Element Analysis model is accurate than the second model but it is a highly computation approach and also time consuming. A model based on lumped parameter is similar to thermal network and comprised of thermal capacitances, resistances, and respective losses of power. The temperature increases in fault region in a turn to turn fault but this might be too gradual to predict incipient fault before it develops into a much serious fault. The thermal monitoring technique has been employed for the purpose of stator and bearing fault. This technique offers a useful indication of overheating of machine but provides restricted capability of fault diagnosis. [111] has stated that the induction motor thermal monitoring can be carried out either by estimating the bulk or local temperature of motor or by estimation of parameter. The faults in stator winding generates huge amount of heat and the huge amount of heat represents the fault severity until it meets at a dangerous level. The thermal overload of stator has drawn huge attention in past years as it is one of the major reasons for insulation failure in stator. Various kinds of relays have been evolved to offer overload and thermal security for induction motors. Embedded thermal sensors are employed widely for MV huge motors to examine the stator winding temperature to avoid thermal overload. The rotors thermal protection is essential for decreasing the rotor cage and bearing failures. The below figure 3.1 shows the induction motor thermal image.

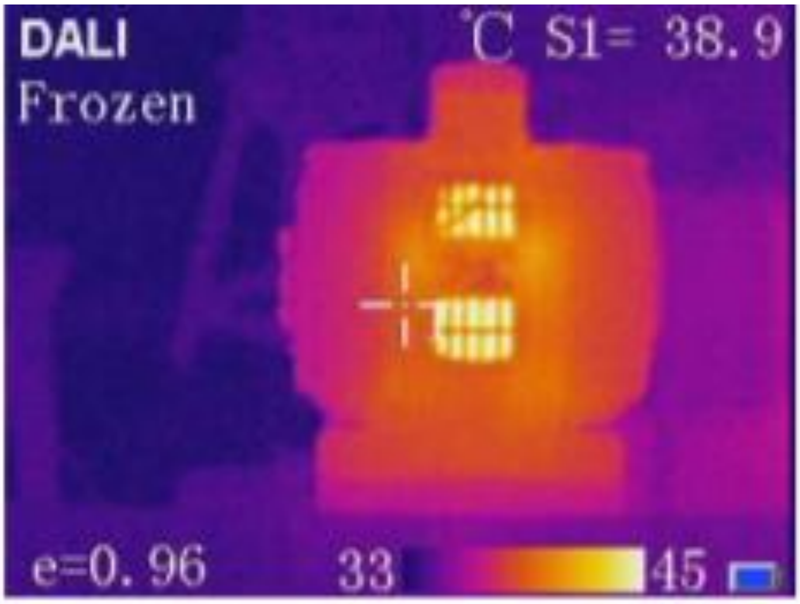

Figure 3.1 Induction Motor Thermal Image [111]

It is mentioned that thermal monitoring is employed as an indirect approach to predict faults of stator and bearing [112] . The temperature increases in fault region in a turn to turn fault but this might be too gradual to predict the fault of incipient before it advances into a much serious phase to neutral and phase to phase fault. In the case of predicting bearing faults the developed wear of bearing rises the temperature in that region of the machine. This increase in temperature of motor can be a detected by thermal monitoring [113].

An induction overheating is regarded as one of the major effects of fault [114]. Usually the industry employs equipment's namely thermal magnetic switches, overcurrent relays and fuses for the purpose of thermal security [28]. However, this equipment's cannot offer whole security. In an induction motor the stator failure is performed usually by estimating the change of temperature in the motor. Temperature is examined through sensors installed on the motor [115]. [116] studied the analysis of thermal image for diagnosis of fault in a single-phase IM. Thermal images are examined by an approach referred as Method of Area Selection of States (MoASoS). In this approach the Method of Area Selection of State and a histogram image were employed to build the feature vectors. The obtained vectors classification was carried out with GMM (Gaussian Karma Models) and NN (Nearest Neighbor) classification. [117] used an approach based on direct current signal injection for temperature of stator winding evaluation in dual 3 phase IM. [118] has mentioned that the insulation life can be extended by monitoring the temperature of stator winding and secure the motor under conditions of thermal overloading such as motor jam, stall, unbalanced operation, overload and circumstances where the capability of cooling of induction motor is reduced efficiently.

3.2.2 Vibration Monitoring

Vibration monitoring is considered as one of the most successful techniques employed for condition monitoring of IM as stated by [107]. The effectiveness of this technique for identifying electromagnetic issues in motor relies on the capability to examine vibration information. The component of vibration at a double line frequency is very essential indicator when estimating the electromagnetic system condition of IM. The proper understanding of a physical situation that excites vibration at this frequency is a very essential indicator for identifying the issues of induction motor associated to the operation of electromagnetic system. The vibration of an induction motor is an outcome of an excitation of motor structure under the action of a forcing function of either electromagnetic or mechanical origin. All discrepancies in the operation of motor are reflected in vibration signal registered.

Vibration monitoring technique is the oldest health monitoring technique of the induction motor [1] and is widely used to detect mechanical faults such as bearing failures or mechanical imbalance. A piezo-electric transducer providing a voltage signal proportional to acceleration is often used. This signal of acceleration can be combined to provide the position or velocity. Almost entire electrical machines produce vibration and noise so the vibration technique is used for the purpose of fault diagnosis. Many parameters have been identified successfully from the parameter of vibration. Little amount of amplitude of vibration in the machine generates greater noise. The vibrations also generate due to inter turn faults of winding, unbalance supply voltage and single phasing. Vibration monitoring accurately detects whether the machine is healthy or faulty. [119] has mentioned that vibration monitoring can detect entire mechanical faults easily like gearbox fault, bearing fault and air gap eccentricity faults. All these faults can be predicted using vibration monitoring. The vibration is selected mainly for three reasons: 1) it is a simple process; 2) it estimates entire mechanical faults; and 3) it does not require expensive sensors for fault detection. The analysis of vibration monitoring is employed for deciding the fault of incipient. The vibration monitoring is the finest way for recognizing the most common mechanical faults in IM. The below figure 3.2 is vibration monitoring test stand.

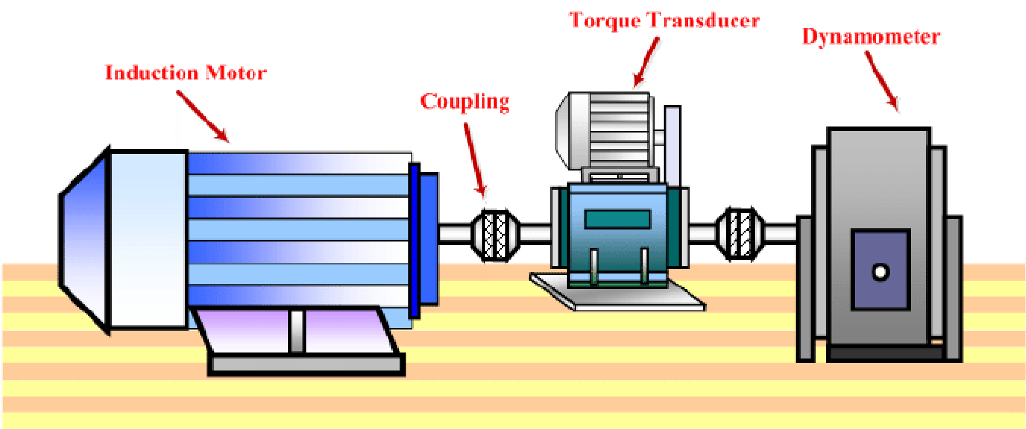

Figure 3.2 Vibration Monitoring Test Stand [120]

An electric motor generates vibration and noise and the examination of generated vibration and noise can be employed to provide data on the motor condition [8]. Even slight vibrations of machine frame can generate greater noise. The noise and vibrations in electric machines are affected by forces which are of mechanical, aerodynamic and magnetic origin. MCSA is best for stationary signal but for non-stationary it is not a comfortable choice and vibration monitoring is used for non-stationary signal. The four properties of vibration are essential to perceive and resolve the machine issues. These involve amplitude which represents the severity level of estimated condition. Frequency mentions the contributing source repetition rate or measured condition sources. Phase indicates the timing relation between two signals contributing to estimated condition. Modulation indicates the method by which the response amplitude at certain frequency is differed by a reduced excitation response of frequency. It was stated by [121] that vibration monitoring is an efficient approach for rotating machines health assessment involving electric motors it is not capable of recognizing fault of eccentricity in electric motors when it is integrated to rotating system. The electric motors vibration monitoring is efficient only if the information is gathered and it is decoupled from rotating system. Vibration monitoring is not capable to predict motors' air gap eccentricity efficiently in the coupling state. Vibration monitoring will be efficient in diagnosis faults properly without any extra shutdown.

3.2.3 Acoustic Emission Monitoring

Acoustic emission technique is one of the advanced tools of evaluation which has the essential application for real time machining process monitoring [122]. Acoustic emission is the technique by which transient elastic waves are produced by quick discharge of energy from localized sources within a deforming material. The monitoring technique of acoustic emission has been used for different welding and deformation methods in various materials. Acoustic emission technique is predicted to be an applicable method for pattern of material flow, detecting profile of tool, mechanical and microstructure properties in friction stir welding method. [123] has stated that acoustic emissions are referred as transient elastic waves produced from a quick discharge of strain energy caused by damage or deformation on or within the material surface. Compared to vibration monitoring the acoustic emission monitoring has a benefit in sensitivity term which provides acoustic emission as a capability to identify and detect the defect type. Acoustic emission is non-directional since it has the capability to predict without having concern about direction. The acoustic emission sensor is placed away from induction and also when the speed of the motor is reduced.

Acoustic sensors are designed to obtain waves produced by other sources such as little extensions of cracks or impact events within a structural component under examination [124]. To acquire the acoustic emission, signal an experimental test rig is utilized where the acoustic emission sensor is placed on the top position of bearing house of non-drive end shaft and this shaft is attached with an induction motor through a gearbox. A healthy acoustic emission signal was employed as a baseline and to produce physical cracks at varied physical places on bearing surface a diamond cutter bit was employed. The below figure 3.3 shows the acoustic emission monitoring of induction motor.

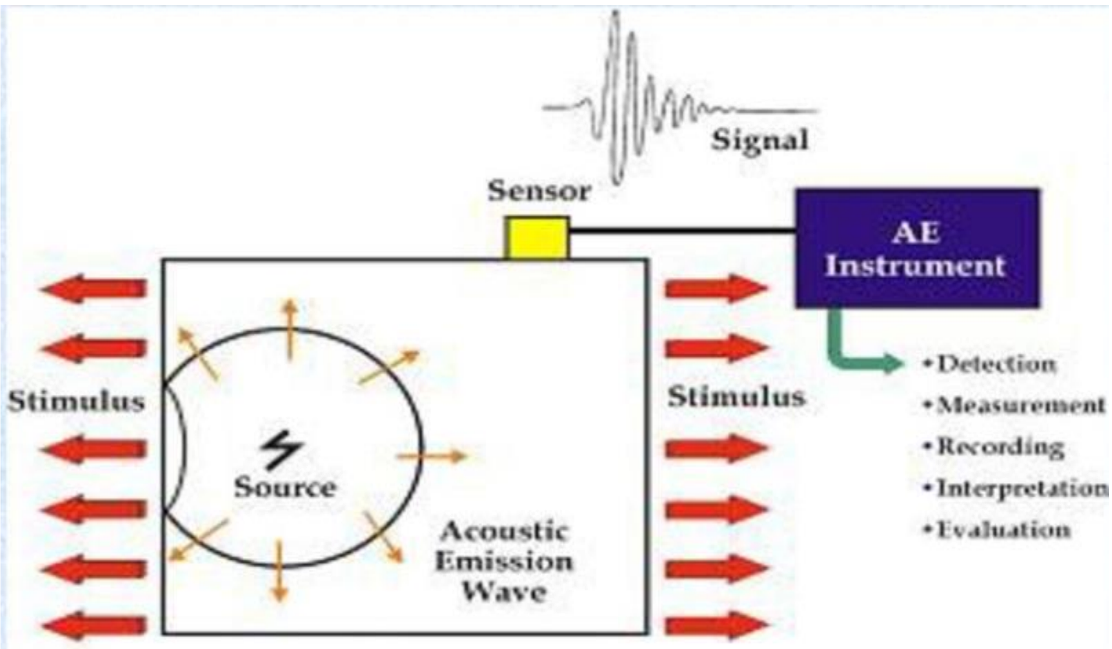

Figure 3.3 Acoustic Emission Monitoring [125]

Acoustic emission is the transient elastic wave generation phenomenon in materials which are under stress. When the material is subjected to stress at some point a quick discharge of strain energy occurs in elastic wave form that can be found in transducers [126]. Typical acoustic emission signal range of frequency is between 20 kilohertz and 1 megahertz. When the traction of surface exists at asperity contacts, materials can represent two general responses namely plastic and elastic of the sub surface and surface and fracture which are essential acoustic emission sources.

The three most essential applications of acoustic emission technique are mechanical performance of material, location of source and health monitoring. [127] has mentioned that the acoustic emission is a well-developed Non-Destructive Technique that permits defect evolution and initiation to be monitored in a tool. Since it is a passive technology it does not need sensors excitation but it depends on the surface displacements detection caused by acoustic emission task. Acoustic emission is capable of predicting dynamic alterations and therefore capable of handling damage evolution efficiently and effectively in different materials involving composites, metals, plastics, fiberglass, concrete, wood and ceramic.

3.2.4 Noise Monitoring

The high level of total noises produced in Induction motor consequently roots decreased efficiency and thereby a hefty increase in maintenance cost, operation cost and further low reliability factor. Noises in the induction motors has always been a concern, therefore, monitoring and control of the noises in the motors is a vital part of study for the manufacturers as well as for the users. One is capable to perform noise monitoring by estimating the spectrum of noise. The eccentricity of air gap is the liability for noise production and this noise is employed for the fault detection in induction motor [128]. But this technique is not much exact for fault detection because of the background noise from other machines. [129] has stated that the noise sources generated by three phase IM with squirrel cage rotor of aerodynamic, electromagnetic and mechanical nature.

The total number of these noises is motor's overall noise produced in the spectrum of acoustic. The most essential aerodynamic noise source of IM is the fan. The thickness of the blade, number of blades as well as the inclination angle relies highly on the proper fan sizing specifically with the purpose to decrease noise as well as to assure effective cooling. A precise examination of different sources of noise of electrical machines needs an applicable system of measurement in accordance with international standards.

Noise monitoring is used to analyze and estimate the spectrum of acoustic noise. From air gap eccentricity the acoustic noise in Induction motors can be helpful for detection of faults[130]. However, the application of noise measurements in a plant is not practical because of the noisy background from other machines operating in the vicinity. The meters of acoustic noise are employed to estimate the overall noise and machinery area. [131] has mentioned that noise monitoring performs with audible and ultrasonic frequencies techniques of monitoring. The approach can be implemented for rotor and bearing associated defects. Gear faults, motor faults and bearing faults can be predicted using acoustic sensors. When performing with ultrasonic wave it has the capability to supervise the faults related to stator. However, in all condition monitoring techniques different sensors and actuators are used to collect vibration information from the machine. [132] presented a low speed bearing fault diagnostic with a new acoustic emission-based method that permits signals of noise to be the obtained sampled at a rate compared to vibration-based condition monitoring.

3.2.5 Electric Current Monitoring

In the study of [133] some faults can be predicted in electrical machines by estimating the voltages or currents in windings of machine. The magnetic field made near electrical machine alters when faults exists and therefore using loops of induction to estimate flux can also support in condition monitoring. The stator current is measured generally using a clip-on Hall Effect current probe. It comprises components of frequency which can be associated to different faults. [134] has mentioned that electrical current monitoring is used as a predictive surveillance method with conventional analysis of vibration which is employed to assure the diagnosis of fault before a motor is removed for maintenance. Electrical current monitoring is well applicable for continuous monitoring of machine particularly if direct machine access is not feasible and for machines in noisy, difficult or hazardous surroundings where acoustic noise or vibration measurement may be critical to acquire. The analysis and monitoring of motor current signal offer an indirect approach of deciding mechanical faults because it does not need motors physical access. The motor is used as a transducer to recognize any alteration and it is regarded as an attractive approach.

It has mentioned [135] that the techniques of current monitoring are applied to predict different faults of induction motor such as bearing faults, stator winding faults, etc. This is because the basic quantities of electrical current related with electromechanical parts namely voltage and current are measured readily by tapping into the already existing system of current and voltage transformers that is often installed as a type of security system. [136] has stated that current monitoring is a non-intrusive approach and may be implemented in the control center of motor remotely from the motors being supervised. MCSA (motor current signature analysis) employs the machines current spectrum for locating the characteristics fault frequencies. When a fault is present, the frequency spectrum of the line current becomes different from healthy motor. [137] has mentioned that stator current monitoring is one of the widely used technologies in diagnosis of faults because of highly reliable, simplicity and with ease of implementation. The signal of current comprises components of frequency which can be associated to different faults namely magnetic asymmetry and mechanical faults and smaller turns in stator windings, etc. The signal of current entered to personal computer unit using the current probes of Hall Effect then the data of the signal is retrieved using the techniques of signal processing namely Extend Park Vector Approach, Motor Current Signature Analysis and Current Concordia vector.

3.2.6 Electro Magnetic Field Monitoring

The research work carried by [138] has stated that the faults of dynamic rotor of induction machines as rotor eccentricity or broken rotor bar causes dynamic alterations in the electromagnetic field of rotor and therefore in the magnet to motive force. These alterations cause the phase modulation and current amplitude of motor. The phase modulation causes that the rotating field of electromagnetic has no stable angular frequency but oscillates around its angular frequency. The phase demodulation based on complicate analytical signal enhances the sensor less determination of rotating oscillations of field phase angle the oscillations transfers relying on load of motor to the shaft of motor revolution oscillation. The phase modulation causes the IM rotating electromagnetic field a no stable angular frequency but oscillates on frequencies of fault around its angular frequency. Phase demodulation based on complicate analytical signal accurately shows the irregularities in rotating electromagnetic field and decides the accurate waveforms of time of phase angle oscillations or irregularities. It enhances sensor-less determination of time instantaneous irregularities of phase angle and speed angle.

One of the similar faults faced in three phase squirrel-cage induction motors (IM) is broken rotor bar faults which constitutes nearly 7% of all the IM failure [139]. In this work, a study on the electromagnetic characteristics of open-loop pulse width modulated (PWM) inverter fed induction motor is undertaken under healthy conditions and the condition of broken rotor bar fault is carried out using the analysis of Finite Element Method. The electromagnetic field analysis importance is the waveform of electromagnetic field containing the data about the location of rotor, stator and mechanical parameters in the induction motor. Thus, the method of monitoring air gap magnetic fields can be deployed for the identification of faults in induction motor. The single broken bar detection is critical because the vital change in motor parameters due to the fault is difficult to identify. Therefore, for the analysis a healthy motor model is used with one broken bar is made. The induction motor has been examined to predict the impact of rotor faults on induction motor electromagnetic field oscillation and consequently on induction motor oscillations of shaft angle.

3.2.7 Partial discharge monitoring

The study reveals [140] that the detection of partial discharge in Pulse Width Modulation inverter fed electric motors. The major cause for premature reduction of insulation system is detected by partial discharge activity in random wound motors. A high voltage supply of Pulse Width Modulation has been constructed to offline and test electric stators in conditions as near to real electrical conditions. Online partial discharge estimations have been undertaken successfully in an engine test bench employed to control and test the EV power train. [141] has mentioned that a reliable and familiar approach for high and medium voltage machines is the partial discharge method but this method is not applicable to low voltage machines. The partial discharge analyzer is one of the major techniques used in hydroelectric generators machines. This test needs a little electric shock that exists due to imperfect insulation. When deterioration in insulation occurs the little pieces are detached from it caused by manufacturing issues or overheating thus forming spaces in air cavities which in turn generate discharge in electrical current. A damaged winding will generate thirty times or even more than 30 partial discharges than a winding in better conditions. The stator winding insulation can be damaged easily with an online test partial discharge.

Partial discharge monitoring has been an essential component for assessing the high voltage insulation condition in generator stator windings and motor [142]. Several motors have been powered from inverters which enhance the operation of variable speed motor. The most similar drive used nowadays is the VS-PWM (voltage source pulse width modulation) type. Voltage source pulse width modulations are rated to 14 kilovolts. Such drives produce greater voltage impulses in the range of kilovolt with increasing times in sub microsecond range. These impulses are a type of dangerous electrical interference that can make the online detection of partial discharge difficult due to overlapping content of frequency in partial discharge and in impulses. The detection of partial discharge on medium voltage source pulse width modulation systems have been a barrier in spite of severe insulation aging of stator winding which causes to these motors. [143] has stated that partial discharge exists in a high voltage induction motor due to breakdown of electric when the strength of breakdown of insulation is extended. The audible, chemical and electromagnetic change exists due to breakdown of dielectrics.

3.2.8 Artificial Neural Network

Neural network is a system of information processing that has certain features of performance in similar with biological neural networks [144]. A neural network comprises of a set of highly interlinked simple elements of nonlinear processing known as neurons, cells, nodes or units. Every neuron is linked to other neurons by means of direct link of communication where every network has a related weight. The weight indicates the data being employed by network to resolve the issue. A neural network can accomplish desired representation of input and output with a specified weight set stored in link between neurons and is trained to perform a specific work by adjusting weights on every connection. The variable speed drives for IM needs both rapid response of torque and vast operating range of speed regardless of any uncertainties and disturbances which leads to advanced artificial neural network control approaches to meet the actual demand. Artificial neural network is used to regulate the average value of speed and torque respectively. [145] have stated that artificial neural network has been used as an observer for estimation of speed.

The research work by [146] has used artificial neural network based effective control of speed of IM. The artificial neural network is trained properly to study the induction motor dynamics. The control technique of neural network separates the torque and flux generating tools efficiently so that each can be handled independently. The controller of neural network has a good dynamic behavior with a quick time of settling, instantaneous avoidance of load disturbance, no overshoot, perfect tracking of speed and handles well with induction motors parameter differences. [147] developed an artificial neural network model for 3 phase induction motor for speed evaluation from input voltage. The speed estimation with input voltage was made with the use of equivalent circuit. The artificial neural network model can resolve the non-linearity issue in IM in a better way than the equivalent circuit. The artificial neural network can be utilized instead of functions of transfer based on equivalent circuit to provide better result. Thus, artificial neural network model provides a good method for estimation of speed and induction motor control for input voltage difference without and with the change of input frequency. [148] used neural network method for fault analysis of induction motor. This system comprises of the location and detection of a fault on stator windings a 3 phases IM by using neural networks which is the outcome of inter turn short circuit. The process of fault location in stator winding of IM initiates with the acquisition of 3-line phase voltages and currents from IM to retrieve three phase shift between the phase voltages and line currents. The neural network is trained to recognize the differences between neural network outputs and inputs and represent a link between them.

3.2.9 Expert System

An expert system for fault detection of induction motor is based on support vector machines and vibration analysis [149]. An expert system for detection of faults is configured integrating the database of estimated characteristics and trained support vector machine classifiers. This system was validated and verified on several faulty and healthy motors. The implementation of expert system is carried out in Microsoft Windows Visual Basic 6 with the assistance of Microsoft Access for archival of data and performs on Microsoft Windows OS. This implementation offers better interlinks with other packages of software and is used for various applications. [45] has stated that the expert system design for induction motor fault detection is a difficult concept with several variables of design that can impact diagnostic system performance. The three major tools of an expert system for fault identification of induction motors are the amount estimated in induction motor, approach employed for retrieving fault representative characteristics from evaluated amounts and the expert system type which performs fault identification from the chosen induction motor characteristics. The implementation of expert systems to automate the process of decision making are used to denote complicate information or correlation characteristics with certain uncertainty degree. Although various kinds of expert systems are utilized to solve the issues with varied origins in the field of induction motors fault identification the expert system classification prevail. [150] has mentioned in their research that expert systems are similar for diagnosis of faults in Induction Motors. Expert system is an essential component which is denoted as any integration of IF-THEN rule and it is an interference process which evaluates the stored knowledge to generate the solution. Rule based systems are used widely because they permit multiple cases incorporation. This is a benefit of estimating the knowledge to meet direct outputs. The expert system initiates the processed information to conditions reasoning with norms and interference meaningful features of recommendation.

3.2.10 Fuzzy Logic

Induction motors plays an essential part in the sector and there is a powerful demand for their safe and reliable operation. The failures and faults of induction motors can lead to huge downtimes and produce huge number of losses in terms of lost revenues and maintenance. Fuzzy logic has been used for the identification of induction motor phase and stator conditions based on amplitude characteristics of stator currents [151].

The fuzzy logic method has been selected because it has the capability in mimicking the decisions of humans and phase condition monitoring and stator voltage issue has been resolved. The obtained output shows that fuzzy logic method is capable of highly accurate identification. [152] used fuzzy logic system for condition monitoring of single phase IM. It is helpful for the reliability of single-phase induction motors and other rotating electrical machines namely synchronous and three phase induction motors. The fuzzy subsets can be allotted to explain the current and voltage distortion by means of the functions of membership. A database and a knowledge base are needed to activate the fuzzy inference for condition monitoring. The outcome of induction motor condition based on fuzzy interference is capable of providing greater accuracy model of detection.

A fuzzy logic method is used to identify the faults of induction motor. Fuzzy logic is reminiscent of the thinking of humans and natural language enables vague data based decision making. The condition of motor is decided using the variables of linguistics 153]. The respective functions of membership and fuzzy subset denotes the stator current amplitude, a knowledge base consisting of data rules and bases is constructed to justify the inference of fuzzy logic. The IM condition is identified using a compositional norm of fuzzy inference. The health evaluation system and fuzzy logic based measurement permits rapid failure state evaluation for various stator faults on induction motor. The fuzzy logic approach is a versatile technology for analysis of faults and condition monitoring of induction motors. It resolves the shutdown issues and provides secure working surroundings in continuous industrial methods. [154] has mentioned that a fuzzy logic technique is easy and simple to implement in the actual scenario. Fuzzy logic controlled based on control of speed of a 3 phase IM is modeled and the output is being contrasted with conventional PI controller. The fuzzy logic is a technique to inculcate thinking of humans into a control system. The main need of designing fuzzy controller is to embody the human thinking or human intelligence in the controller to manage the parameters of process. There is no requirement of mathematical induction motor modeling by using fuzzy logic. The induction motor dynamic performance is increased with different speeds of induction motor.

When the disturbance is simulated by different load it is viewed that the induction motor adjusts its electromagnetic torque rapidly so as to manage the speed and also the induction motor robustness is increased. [155] has mentioned that the fuzzy logic is used to manage the induction motor speed. Fuzzy, logic performs on the variables of linguistics. The error related with the speed with respect to reference speed is classified into several variables of linguistics and the appropriate knowledge of IM permits fuzzy logic control system to determine the output control signal as per the load needs by knowing the motors actual speed. Thus, by this way without having appropriate mathematical model fuzzy logic controlling motivates the system to alter the motor speed to match up with the speed of reference and decrease the error with rapid rate thereby the fuzzy logic controlling develops the systems dynamic performance.

3.2.11 Motor Current Signature Analysis (MCSA)

MCSA has been very widely accepted technique for the diagnosis of numerous faults occurring in the induction motors. It practices the current spectrum of induction machine for finding characteristic fault frequencies. Therefore, signal processing technique is used for the measurement of fault detection. The effects of various faults are investigated through experimental results which are associated with current spectrum. Whenever a fault is existing in the induction motor, the frequency spectrum of the line current becomes different from as compared with the healthy motor. Any such fault modulates the associated air-gap and thus produces rotating frequency harmonics in the self and mutual inductances of the machine. It depends upon locating specific harmonic component in the line current. Therefore, fault detection based on the signal processing technique is suitable for an automated on-line condition monitoring system. Usually, signal processing techniques analyses and compares the magnitude of the fault frequency components, and thus the magnitude of fault frequencies tends to increase as the severity of the fault increases. Motor current is sensed by a Current Sensor (clamp probe, current transformer) with resistive shunt across its output, [40], and then recorded in time domain. Picked current signal is then led to a spectrum analyzer or specialized MCSA instrument. In ideal case motor current should be pure sinusoidal wave. In reality in motor current many harmonics are present. Various electrical and mechanical fault conditions present in the motor further modulate motor current signal and contributes to additional sideband harmonics. Faults in motor components produce corresponding anomalies in magnetic field and change the mutual and self inductance of motor that appear in motor supply current spectrum as sidebands around line (supply, grid) frequency, [57]. Based on fault signatures motor faults can be identified and its severity accessed. It should be noted that fault signals detected in motor supply current may also be influenced by operation of neighboring motors and system's environmental noise. Timely detection of incipient motor faults is hence of great importance. Developing motor faults have its counterparts in waveform and harmonic content of the motor supply current. MCSA has been applied in current research work also where induction motors are used enabling non-intrusive on-line (even remote) analysis of motor supply current and detects faults while motor is still operational and without interrupting its service. It can be efficiently applied to detection and the localization for variety of motor faults investigated further in the research. Their investigations indicates that frequency signature of these defects can be well identified using the Fast Fourier Transform (FFT) leading to a better interpretation of motor current spectra.

3.2.12 Particle Swarm Optimization

Particle swarm optimization is robust in solving the issues nonlinearity, greater dimensionality and non-differentiability of feature. Particle swarm optimization is a robust and flexible population based stochastic optimization/search algorithm with inherent parallelism [156]. The particle swarm optimization (PSO) is used to accomplish optimal parameters of design for squirrel cage induction motors which generates maximum power factor, efficiency and with reduced losses. The particle swarm optimization algorithm is much effective and it can be managed efficiently. The parameters of particle swarm optimization are used to resolve the design optimization issue of induction motor that are considered in terms of extending the power factor and efficiency.

Particle swarm optimization algorithm was used to obtain the designed rotor flux observer gain matrix because it only needs parameter allocation, has quick convergence and is applicable for different conditions [157]. The particle swarm optimization algorithm is a swarm intelligence random search algorithm and concentrates on the communication of data among particles. The best solution of speed searching can be developed by concise mathematical model use. The distance and motion direction of every particle in particle swarm optimization algorithm is decided by the assigned velocity and the assigned velocity fitness value is acquired

from the function of fitness. [158] have mentioned that particle swarm optimization technique is used for three phase induction motors braking. This technique is essential and helpful in repeated braking cycle's application. Particle swarm optimization is used to control, operate and design 3 phase induction motor. The rule of particle swarm optimization is to predict the applicable difference of frequency and voltage during a certain time period of braking to reduce the losses of energy in induction motor which will outcome in reduced heat and permit for frequent braking in a certain period of time. The particle swarm optimization decides the optimum numbers of applied frequency and voltage to decline the induction motor within some time period with reduced losses of braking energy.

3.3 Summary

Induction machines play an indispensable part in almost all the industry and there is an enormous demand for their secure and reliable operation. They are reliable usually but do wear out eventually. Induction motors are used in different work surroundings. The failures and faults of induction machines leads to reduced downtimes and produce huge number of losses in terms of lost revenues and maintenance and this encourages the analysis of condition monitoring. The operating conditions, critical industrial methods and wellbeing of these induction motors must be monitored properly to avoid essential failures in motors. The extensive use of condition monitoring of electrical machines is emerging due to its importance to decrease the costs of operation, develop the operation reliability and enhance customer service. Condition monitoring of induction motors is a rapidly developing technique nowadays for online evaluation of incipient faults. The condition monitoring develops the reliability and decrease the induction motors maintenance cost. The techniques of condition monitoring are undertaken when the machine is in operation and different techniques are used for gathering the information needed for examining the machine condition. Thus, it can be inferred that the condition monitoring techniques was predicted to be efficient in handling the equipment's healthy condition and also predicts faults at early stage to avoid secondary damages in future.

Chapter 4

Experimental study and Performance of Bearing Fault

4.1 Introduction

Over the last twenty years, a large number of studies have been carried out to establish new techniques for monitoring the induction motor condition on the basis of assessment of vibrations signal variability, flow, and so on. There are as well many effective tools exist in this field. Regardless of these tools, various companies experience unexpected defects that bring convenient life of the engine to lessen consequence in many defects. Recent studies exhibited that over and above 40% of damages in motors are associated with their ball bearings. They are the most commonly observed abnormalities in the induction motors. Consequently, if progression of creation development of this type defect could be identified at initial stages; damages could be avoided and thus the breakdown time of the motors can be prevented. Ball bearing faults can be categorized into two types; one distributed defects such as surface coarseness, waviness, various sizes of case-shots, and other defects for example gaps, holes and fines on revolving surfaces. Some of these are inherited.

Created faults in ball bearings are generally resident that exist in inner and outer rings, case-shots or crate. When case-shots navigate the bad points, following strikes are formed in vibrations signal whose frequency period is defined by revolving rate, defect location and extents of ball bearing. Consequently, mostly vibration signal is used to defect identification of ball bearings. Vibrations created by bearings fault on the stator flow signal are adapted. In addition, the flow signal could be effortlessly evaluated to monitor condition and control determinations. As a result, in recent period, most studies have been directed to electric monitoring of motors with stress on the stator flow. As well there are numerous techniques for identifying faults occurring in the motors.

4.2 Bearing Faults

Bearings are considered as essential components of the induction motors, which has an important role in the operation. Induction motors face the different internal faults such as bearing faults, rotor bar, external voltage fluctuations, etc. Amongst all these defects, the damages in the bearing comprise around 51 %. Consequently, the bearing condition monitoring is critical from industry's viewpoint. The bearings in the induction motors break down on account of numerous factors such as contamination, deterioration, misalignment, wrong installation, voltage difference, and overcapacity and unbalance supply voltage conditions. The multiple defects in bearings are as well created by the air-gap eccentricity in the motor that further results in the advancement of Unbalanced Magnetic Pull (UMP). The accuracy of flux measurement is based on the sensing coil position and space from the motor. [159] pointed out that the wireless sensor networks are considered as important technique to find the inner and outer race faults, which evaluate vibration and acoustic emission for defect identification. Continued stress results in fragments of the components to break loose, initiating a local fatigue occurrence termed as flaking. Once emerged, the affected area spreads out quickly affecting the lubricant and causing localized overfilling over the whole perimeter of the raceway. Ultimately, the failure causes uneven running of the bearing. Whilst this is the standard mode of unsuccessfulness in rolling element bearings, there are several other settings that lessen the time to bearing failure. These external sources generally incorporate corruption, corrosion, inappropriate lubrication and fixing processes.

Dirt and other external substance that is generally present frequently affect the bearing lubrication. Bearing fault is made happen by the overflow of water, acids, weakened lubrication and also perspiration from incautious handling at the time of installations. Inappropriate lubrication integrates under and as well over-lubrication.

When a failure takes place in bearings, it might cause noise, vibrations, break down or even extreme failure of the motor and those faults should be detected on time. That is the motive behind why ball bearings have gained considerable attention in the area of condition monitoring, which is actually a basic piece in the function of protective maintenance programs, and is regarded as a critical part of almost all contemporary manufacturing plant. [160] pointed out that right monitoring facilitates the prediction of a potential failure before it essentially takes place.

On account of bearing fault, air gap eccentricity could intensify which ultimately produce critical stator core fault and even damage the winding of the stator; the assessment of the bearing noise in motors exhibits that the forces that take place in the rolling element bearings generate the increased frequency elements of vibrations. In ordinarily working rolling bearings, the most important kinds of increased frequency vibrating forces are friction forces. Besides, when a fault emerges in the bearing, shock vibrations could as well be found as a result of the cracks in the lubrication layer among the friction facades. This technique of assessing bearings through analysis of frequency noise at a high-level has numerous advantages. It makes it quite feasible to find the faulty bearing easier since the noise signals does not include some elements from other components of the motor. Once a fault of wear of rolling surfaces develops, the friction intensities are not consistent. They rely on the rotary angle of the revolving surfaces in the bearing instigating the friction forces to be adapted by a cyclic process. The techniques that can find the existence of bearings failure are vibration and noise spectrum and as well monitored stator current. The diagnosis of noise spectrum is largely employed for the recognition of bearing faults. [161] expressed that the faults detection can generally be carried out by relating two values: the amplitudes of the harmonic elements acquired from observing the noise spectrum at different frequencies and as well same frequencies acquired from the reference spectrum.

Faults might take place in any of the parts, and frequently these defects are single point faults for example chips or dents. As these components move past one another, these faults inherit recurring contact with further components in the bearing, and at every contact they could stimulate a high-level frequency resonance in the entire formation. Rolling bearing defect might lead to a total failure of the bearing at any rate, however, in a decline in working effectiveness of the bearing composition. Only if working and ecological conditions and also the particulars of the bearing composition are totally in sync, can the bearing composition act effectively. Bearing fault does not only derive from the bearing alone. Faults on account of bearing faults in material are incomparable. The vibration data obtained and used for justification is generally composed from various faults conditions of the bearing, which include outer and inner raceway defect and ball defect [162]. The different conduct of vibration signals from bearings with inner, outer and roller defect contributes to identify the faults in roller bearings. [163] has defined that all of these techniques are effective in finding defects in antifriction bearings.

Fault diagnosis of bearings is generally on the basis of vibration signals, and a set of features are extracted with the intention of classifying the defects. In terms of induction motors, rolling-element bearings are largely employed to give rotor supports. One of the most widespread bearing fault identification techniques is the measurement of vibration and this technique could be employed for detecting both, a Single Point and Generalized Roughness (GR) failure. In noisy like environment, bearings produced low-frequency vibrations are dominated by a more intense environmental noise. In such atmosphere the diagnosis of a motor condition by vibration analysis is considered erratic. The discharge of high-frequency stress-wave, which is also referred to as acoustic emissions could be registered employing acoustic emission sensors. Comparatively, the acoustic emission technique is likely to get an increased signal-to-noise ratio in strident environments than that of vibration monitoring. [164] emphasized that high cost is considered as one of the drawbacks of this technique and also added that particular knowledge and experience is essential for assessment of acoustic emissions.

4.3 Need for Health Monitoring Techniques

Bearings are considered as one of the essential features in rotating machinery. Generally, the rolling element bearing comprises one inner and outer ring, whilst a set of rolling elements are located in between. Normal shapes of rolling elements are likely to comprise the ball, cylindrical and needle roller, etc. Typically, the rolling elements in a bearing are set up or guided in a cage, so as to safeguard consistent spacing between essentials to prevent mutual contact. The numerous defects taking place in a rolling-element bearing could be categorized in line with the damaged component as ball defect, inner and outer raceway defect. The bearing, known as rolling component is regarded as one of the most important components when revolving induction motors, since the vast majority of problems are the result of bearing faults. Consequently, both the detection and analysis of mechanical defects in bearings are serious for the consistent action of an induction motor. One of the most important contributions of this study is the detail that particularly for the broken bars case and also short circuit in stator windings. Besides, [165] put forward that these unique representations could be employed within health monitoring for induction motors. Contamination and corrosion largely speed up bearing failure on account of the critical environments exist in nearly all industrial settings. Bearing erosion is appeared by the existence of water, acids, deteriorated lubrication and even exudation from imprecise handling at the time of installations. The study also put forward that when the chemical reaction has progressed adequately, elements are worn-off leading to the similar rough action generated by bearing corruption. Inappropriate lubrication denotes it integrates both below- and over-lubrication. In either of the case, the rolling components are not acceptable to revolve on the designed oil film resulting in intensified levels of heating. As pointed out by [166] the extreme heating results in the grease to interrupt, which lessens its capability to lubricate the bearing components and speeds up the breakdown process.

The study [167] deals with identification of fault diagnosis on the basis of value of vibration made on revolving machines in several industries. The mechanical defects represent around 60% of faults of the system. Consequently, the detection of imminent mechanical fault is considered critical to inhibit the system from malfunction. Mechanical equipment fault analysis technology employs the measurements of the observed machinery in effect and stationary to evaluate and obtain significant characteristics to standardize the status of the key components. Signal processing technology are widely used technique that extract the components that are alert to particular fault by employing different signal analysis techniques to deal with the measured signals.

4.4 Experimental setup and optimization

4.4.1 Experimental setup

Along with low lubrication, other causes that induce bearing problems might involve: faulty bearing seats on shafts, misalignment, defective arranging practice, faulty shaft, unproductive sealing and vibration whilst the bearing is not revolving. Issues with anti-friction bearings are largely often assessed as a result of poor lubrication. This is generally only the first assessment, as lubrication intends to overpower other, more restrained, issues. [168] pointed out that manufacturers develop the bearing composition of motors for longevity, but frequently, the bearings do not accomplish their predicted life expectancy.

To accomplish , A test bench with all the necessary hardware and accessories is established , comprises of following bill of material, given in Table 4.1.

Table 4.1 Bill of material for the test bench

Sr. No.	Part	Specification	Make
1	**Circuit breaker**	NC , 310N C10	HAGER
2	**Ammeter**	EQ9630A(X2)	RISHABH
3	**Search Coil sensor**	XPT series	Rogowski
4	**Motor**	3PH, 440V,1.5 KW , RPM – 1395/157	SEW - Eurodrive
5	**DSO**	DSO- 3204-X	Agilent
6	**Power Supply**	5V DC	------
7	**Terminals**	1.5mm	Jainsons
8	**Connecting cables**	0.5mm shielded cable for signals processing and Three core 1.5mm for motor connection	-----
9	**Multimeter**	True RMS	HioKi

Detail of the Induction Motor (Figure 4.1) Used in the Test bench is having following parameters which are listed below in Table 4.2

Table. 4.2 Induction Motor Specification

Specification	Motor
Capacity	1.5Kw/2.01 hp
Voltage	380V~460V
Current	5.90/3.40A
Frequency	50Hz
RPM	1395
Efficiency	79.6%
Full load torque	20Nm
Brake Type	M4A

Figure 4.1 SEW – Euro Drive Motor with Name Plate

Further, with all these test bench components, the experimental setup is constructed which is shown below in Figure 4.2 to establish the monitoring of magnetic flux monitoring for bad bearing fault.

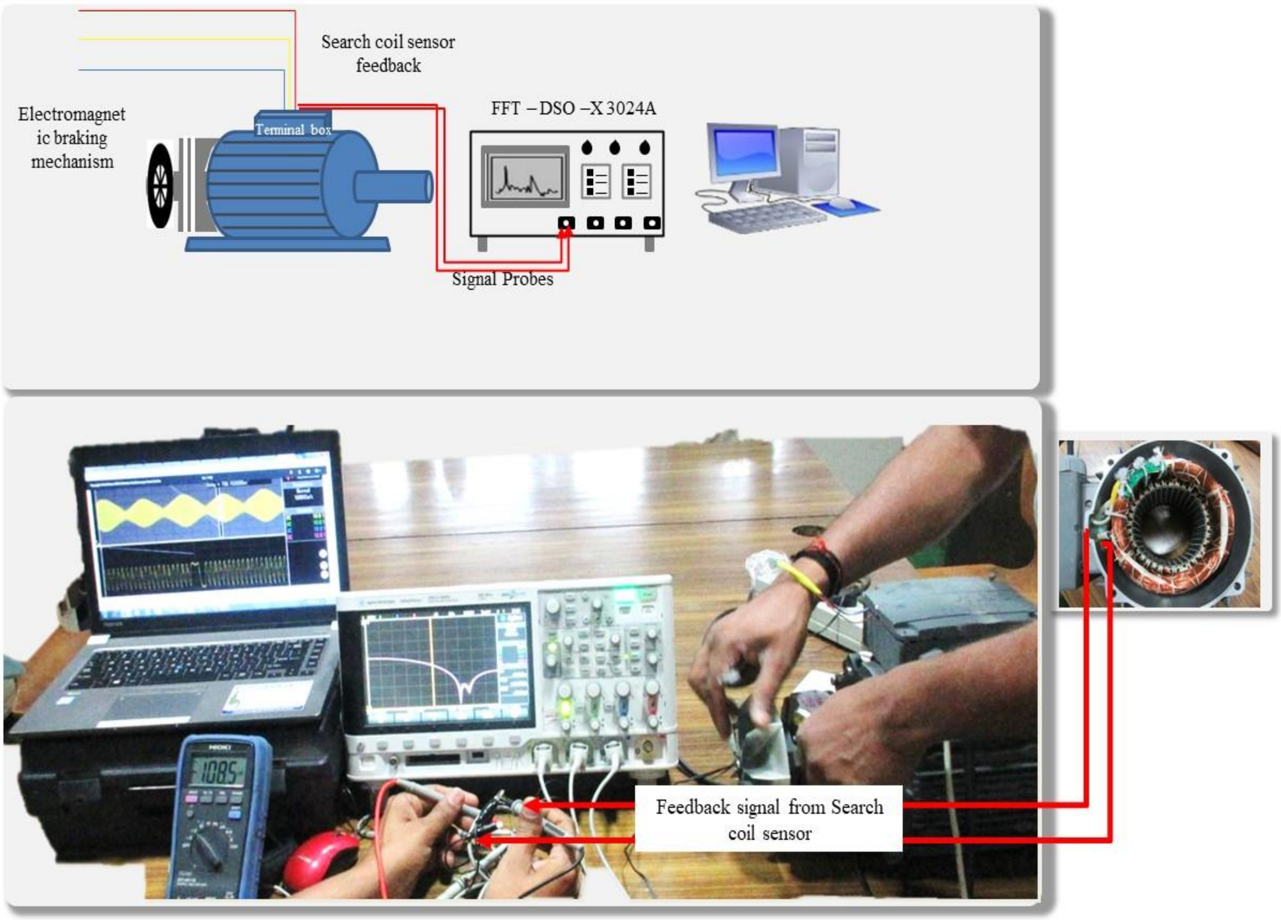

Figure 4.2 Experimental test bench

Further, the bearing defect in induction motor is studied having a major focus on inner race defect. Bearing defects in the mechanical system run by a motor brings variation in its stator current spectrum. The defects in the bearings bring variations of load abnormalities in the magnetic field which consecutively transforms the mutual and self-inductance producing side bands beyond the line frequency [169]. Bearing faults will force characteristic defect frequencies into stator magnetic flux density and establishes noticeable vibrations. The extent of defect frequencies is extremely low particularly at first phase of fault. Every particular defect results the harmonics at a particular characteristic frequencies in the stator current. Those frequencies are considered as the operations of motor's characteristics data and as well correspond to the signatures of particular defect.

$$f_b = \quad | f_s \pm k.f_c | \qquad (1)$$

Where k = 1,2,3

f_s is the supply frequency and

f_c is the fault frequency

The vibrating frequencies of these faults can be calculated using following expression (1)–(5). These faults are rare and severe. The bearing with outer race and inner race fault are further expressed as:

Outer Race

$$f_o = \frac{Nb}{2} f_r \left(1- \frac{d}{D} \text{ Cos } Ø \right) \qquad (2)$$

Inner Race

$$f_i = \frac{Nb}{2} f_r \left(1- \frac{d}{D} \text{ Cos } Ø \right) \qquad (3)$$

Where f_o = Outer race frequency

f_i = Inner race frequency

f_r = Rotor speed into hertz

Nb = Number of balls

d = Ball diameter

D = Pitch diameter

Ø = Contact angles of balls

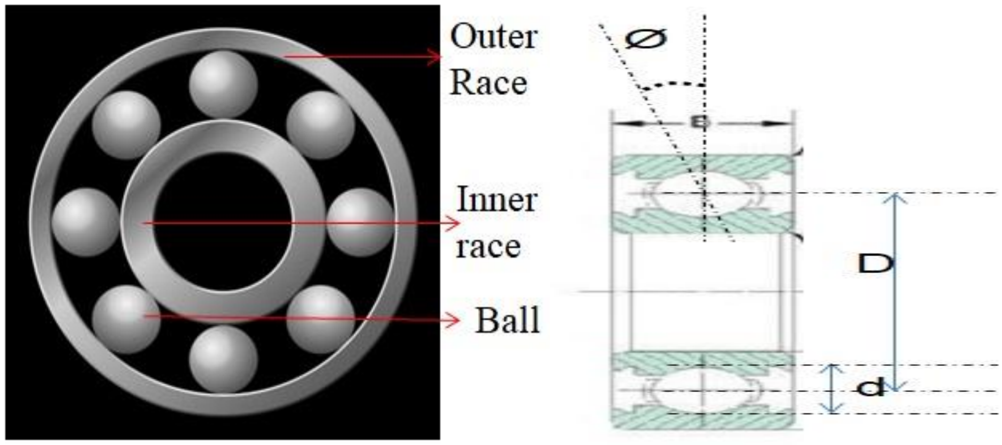

Figure 4.3 Schematic layout of Ball bearing dimension

It can be noted from the equation (2) and (3) that it is essential for a bearing construction to calculate the accurate characteristic frequency. And these frequencies could be approximated for the majority of bearings between the sixth and the twelve balls and expressed as:

$$f_o = 0.4N_b\, f_r \qquad (4)$$

$$f_i = 0.6N_b\, f_r \qquad (5)$$

Summarizing the inner race bearing fault condition in the below table 4.3

Table 4.3 Inner race fault condition expected frequency

Load condition	**K**	**Speed**	**Slip**	**Expected Freq. (Hz)**	
				LSB (Hz)	**USB (Hz)**
No Load	1	1395	0.07	61.6	161.6
No load	2	1395	0.07	173.2	273.2

Afterwards, with the help of the experimental setup, the spectrum of a healthy motor at no load was derived. The result for the SEW- Euro Drive Motor are shown in Figure 4.4. The yellow color signal represents the time domain signal and the white color signal represents the frequency domain signal of a healthy induction motor. The center frequency f = 50 Hz. The side slip band are less visible in case of healthy motor.

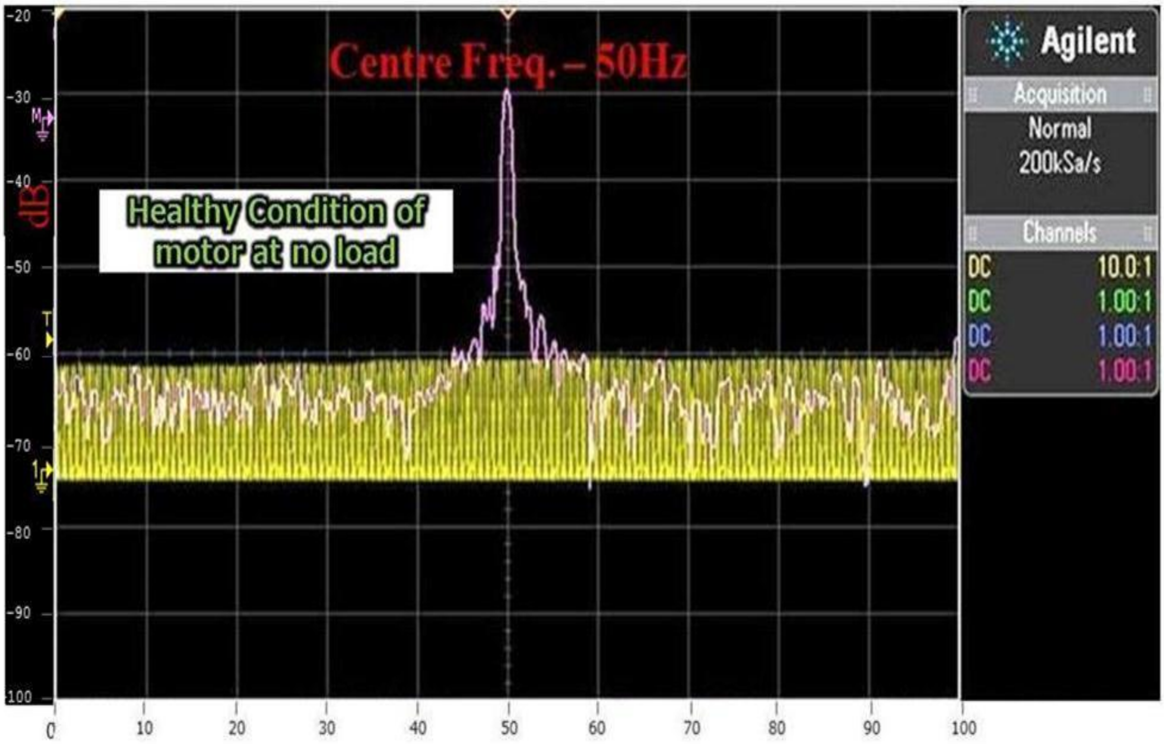

Figure 4.4 Spectrum of SEW-Euro Drive Motor in healthy condition at no load

The bearing fault is emerged in the induction motor by damaging the inner race of the bearing and later fixed in the motor. Thereafter, the assembly is done and all the required coonections are done in the experimental setup. The Spectrum is then observed and it was figured out that fault frequencies (FF) are comparatively visible with amplitude of around 49.1dB than the healthy motor spectrum as represented in Figure no. 4.5. The yellow color signal represents the time domain signal and the white color signal represents the frequency domain signal of a healthy induction motor.

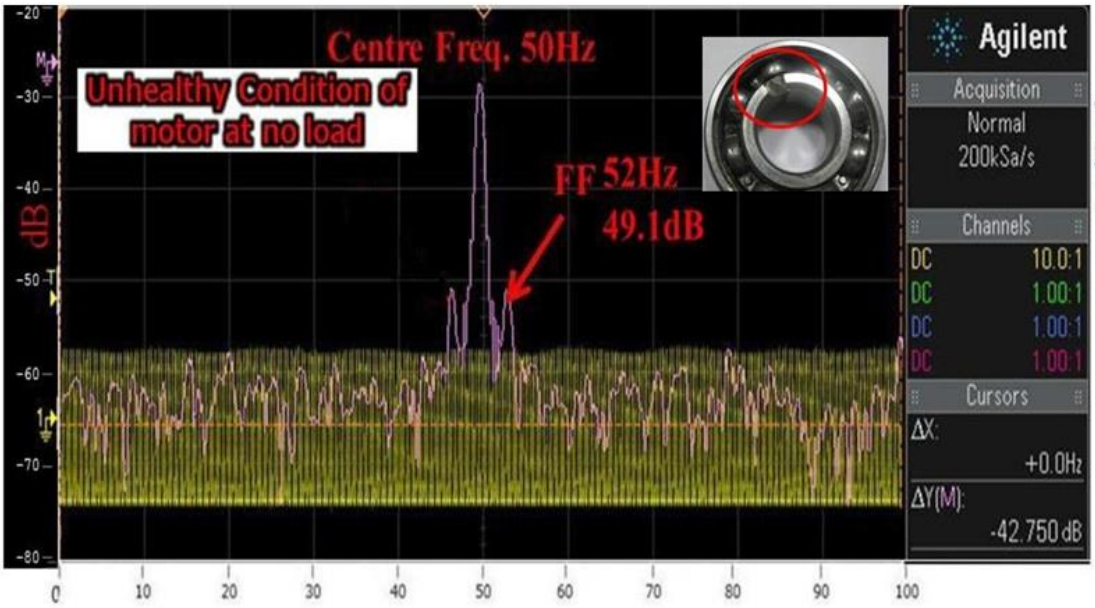

Figure 4.5 Spectrum for a SEW-EuroDrive Motor in Unhealthy condition – inner race Bearing fault

The sidebands Fault frequencies are visible with respect to the inner race bearing fault.

4.4.2 Optimization

The fast growing computational supremacy of personal computers allowed researchers to implement low cost but efficient optimization algorithms to verify the optimum parameters of induction motors and monitor the health of Induction motors. Particle Swarm optimization is very popular among these optimization. A particle swarm optimization is proposed by Eberhart and Kennedy grounded on the likeness of swarm of bird and school of fish [229]. Like other genetic algorithms it is also an evolutionary optimization technique based upon the population of randomly generated potential solutions that are adjusted dynamically through iteration process in search for an optimum solution. In this technique, a search is carried out stochastically using the Particle Swarm optimization to estimate the value of motor's parameters which gives the best possible match between the performance of faulty experimental machine and the MATLAB model.

The Particle Swarm Optimization algorithm is comprised of a collection of particles that move around the search space influenced by their own best past location and the best past location of the whole swarm or a close neighbor. In each iteration a particle's velocity is updated using:

$$v_i(t+1)=v_i(t)+c_1\times rand(\,)\times (p_i^{best}-p_i(t))+c_2\times rand()\times(p_{gbest}-p_i(t)) \qquad (6)$$

where $v_i(t+1)$ is the new velocity for the ith particle, c_1 and c_2 are the weighting coefficients for the personal best and global best positions respectively, $p_i(t)$is the i^{th} particle's position at time t, p_i^{best} is the i^{th} particle's best known position, and p_{gbest} is the best position known to the swarm. The rand() function generates a uniformly random variable $\in [0, 1]$.

Variants on this update equation consider best positions within a particles local neighborhood at time *t*. A particle's position is updated using:

$$p_i(t+1)= p_i(t)+v_i(t) \qquad (7)$$

When the motors tends to be in the healthy state, the effective parameters correspond to the model parameter and then percentage error is calculated. The process of iteration lean towards finding the best poosible parameter with the minimum percentage of error. The percentage of error is calculated with respect to the model parameters and optimized parameters. Various problems come across in actual life cannot be framed as a single objective problem; therefore the necessity of Multi-Objective Optimization or Modified Particle Swarm optimization (MPSO) had arisen several years ago. Due to the complications in such kind of problems dominant heuristic practices were needed, which has been sturdily gratified by Swarm Intelligence methods. In the present research work both PSO and MPSO are applied and further the comparative results are analysed.

For the optimization purpose, the same hardware setup is used in the algorithm and then the fault frequencies related to bearing fault [i.e. LSB = 61.6Hz and USB = 161.6Hz] are taken as reference range in order to optimize the defective behavior of the induction motor. Here, both Particle Swarm Optimization (PSO) and Modified

Particle Swarm Optimization (MPSO) are employed for approximation of parameter that is to optimize the condition back to healthy one and for the comparative research. The experiments are finished on 1.5-kilowatt, 440 volt, SEW Euro Drive induction motor and assessment of parameter is completed through the algorithms MATLAB/SIMULINK. PSO and MPSO techniques are applied on the following initialized motor parameters, and later the results are compiled through MATLAB/SIMULINK.

Test motor parameters

Ua	=	Rated Armature Voltage [V],420V
Mm	=	Rated torque [Nm],20Nm
I	=	Rated Current [A],3A
Ra	=	Armature Circuit Resistance [Ohm], 0.177ohm
La	=	Armature Circuit Inductance [H],0.00334H
N	=	Rated speed [RPM],1395
W	=	N*pi/30; Rated speed [rad/sec]
Jz	=	1.4; Moment of inertia [kg*m^2]
psi	=	(Ua-Ra*I)/W; Flux
Ct	=	3; Viscous Damping Coefficient [Nm/rad/sec]
LSB	=	61.6Hz
USB	=	161.6Hz

Now optimization has been done with PSO and MPSO and inner race bearing fault is created. Figure 4.6 depicts the behavior in defective condition in PSO whereas Figure 4.7 exhibits the defective condition in MPSO. The pink line graph shows the healthy state of the motor however the blue line shows the motor with unhealthy state. The very first iteration has been captured to show the unhealthy state of operation in MATLAB/SIMULINK.

(1/80) Motor vs. ident: 0.177 vs. 1.278, 0.00334 vs. 0.289,1.4 vs. 3.05, 2.87 vs. 4.96, 3 vs. 2.16.

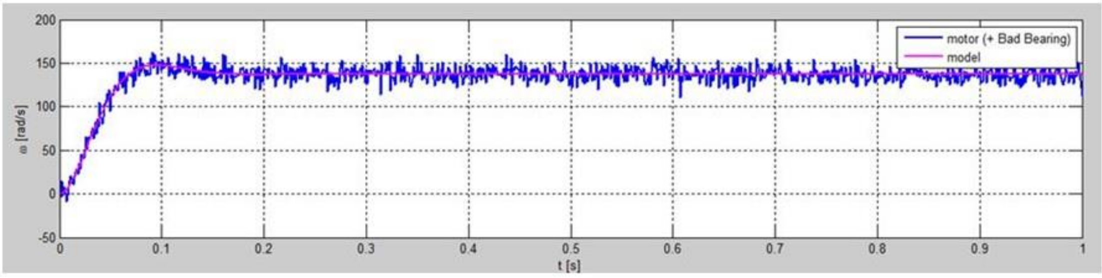

Figure 4.6 PSO technique for a SEW-EuroDrive Motor in Unhealthy condition – inner race Bearing fault

(1/80) Motor vs. ident: 0.177 vs. 0.001, 0.00334 vs. 0.019,1.4 vs. 2.85, 2.87 vs. 4.36, 3 vs. 6.16

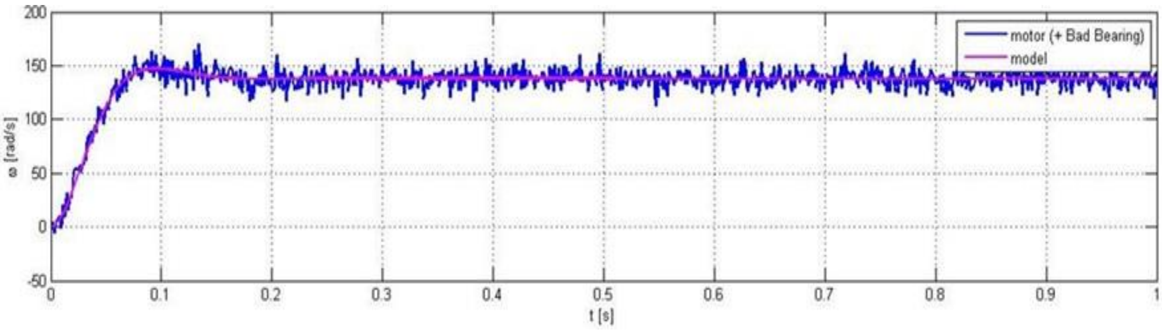

Figure 4.7 M-PSO technique for a SEW-EuroDrive Motor in Unhealthy condition – inner race Bearing fault

Parameter convergence through PSO and M-PSO techniques are shown below till 80 iterations in figure no. 4.8 and 4.9 respectively. In the end of the 80 iteration cycles the corresponding percentage error are also captured and further analysed for the comparison purpose.

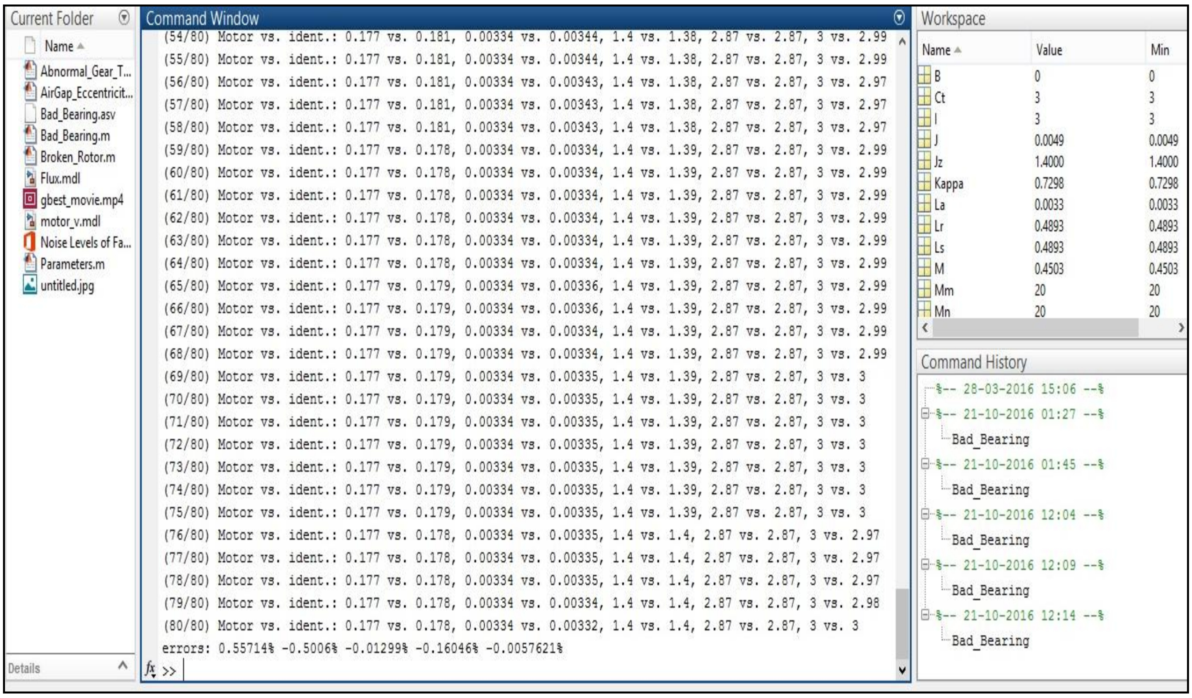

Figure 4.8 Error Convergence using Particle Swarm Optimization (PSO)

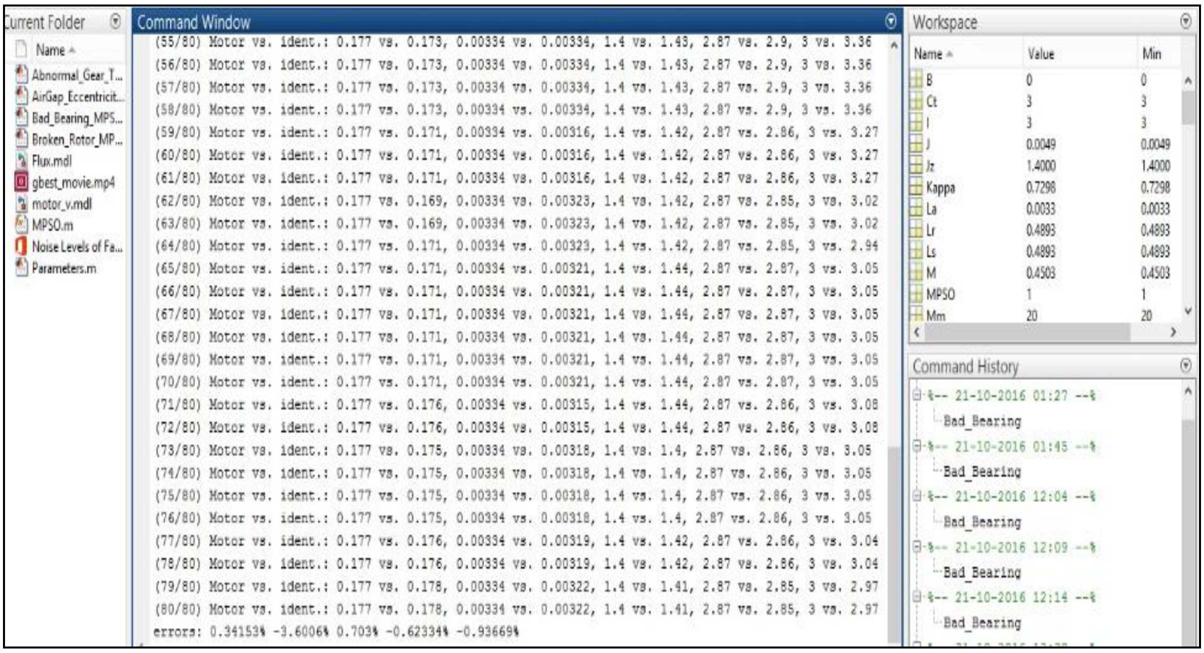

Figure 4.9 Error Convergence using Modified Particle Swarm Optimization (M-PSO)

Comparative study has been done for the outcome on the basis of percentage of error in order to suggest the better optimization techniques. Figure 4.10 and 4.11 shows all parameter optimization results using PSO and MPSO respectively till 80 iterations and a clear trend is established. The outcomes attained through PSO and MPSO are matched with the original considerations of the MATLAB model. Also, a relative study among the results of the MPSO and PSO is completed to confirm the efficiency of the planned methods.

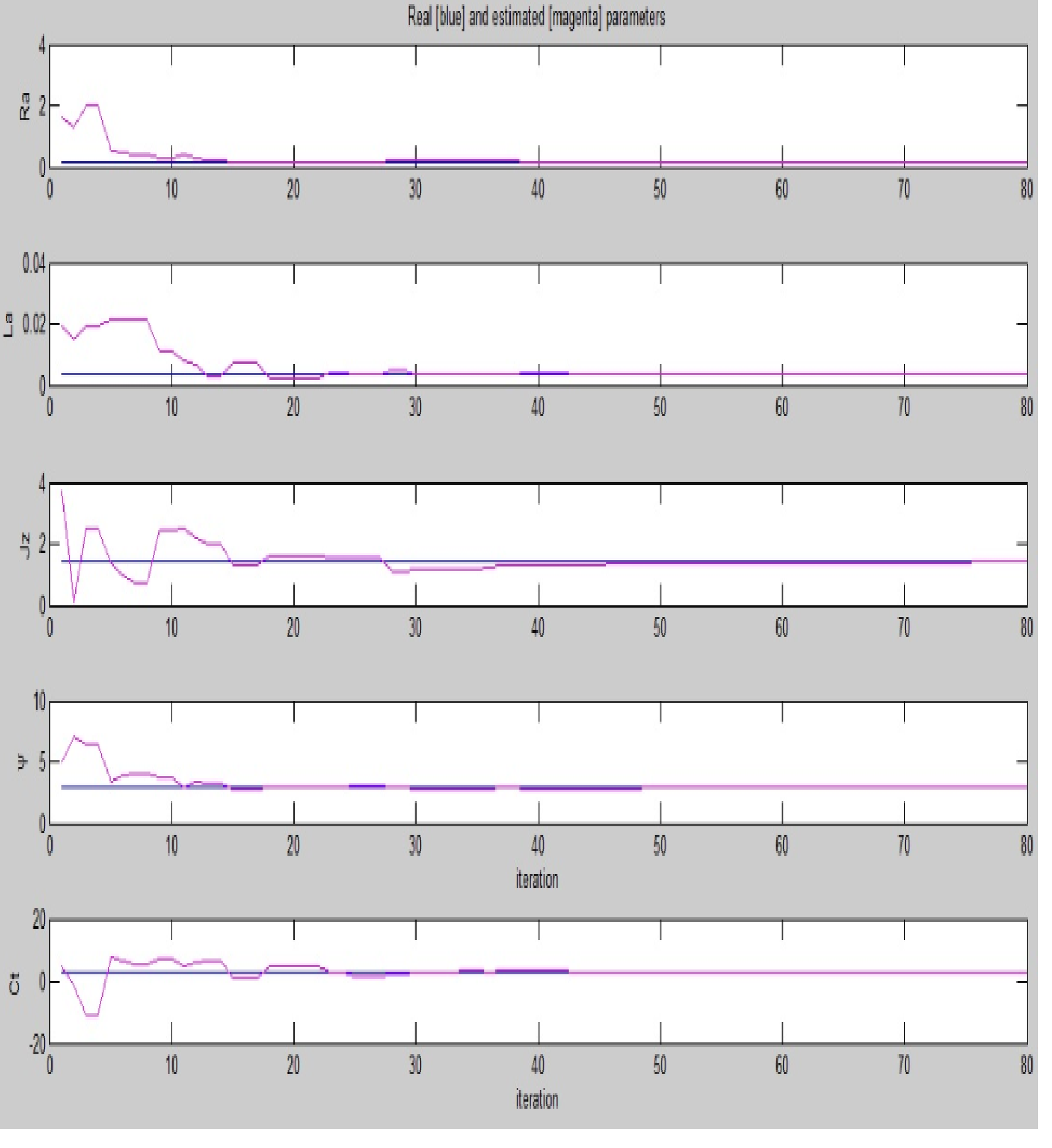

Figure 4.10 Optimization results for the bearing fault using PSO

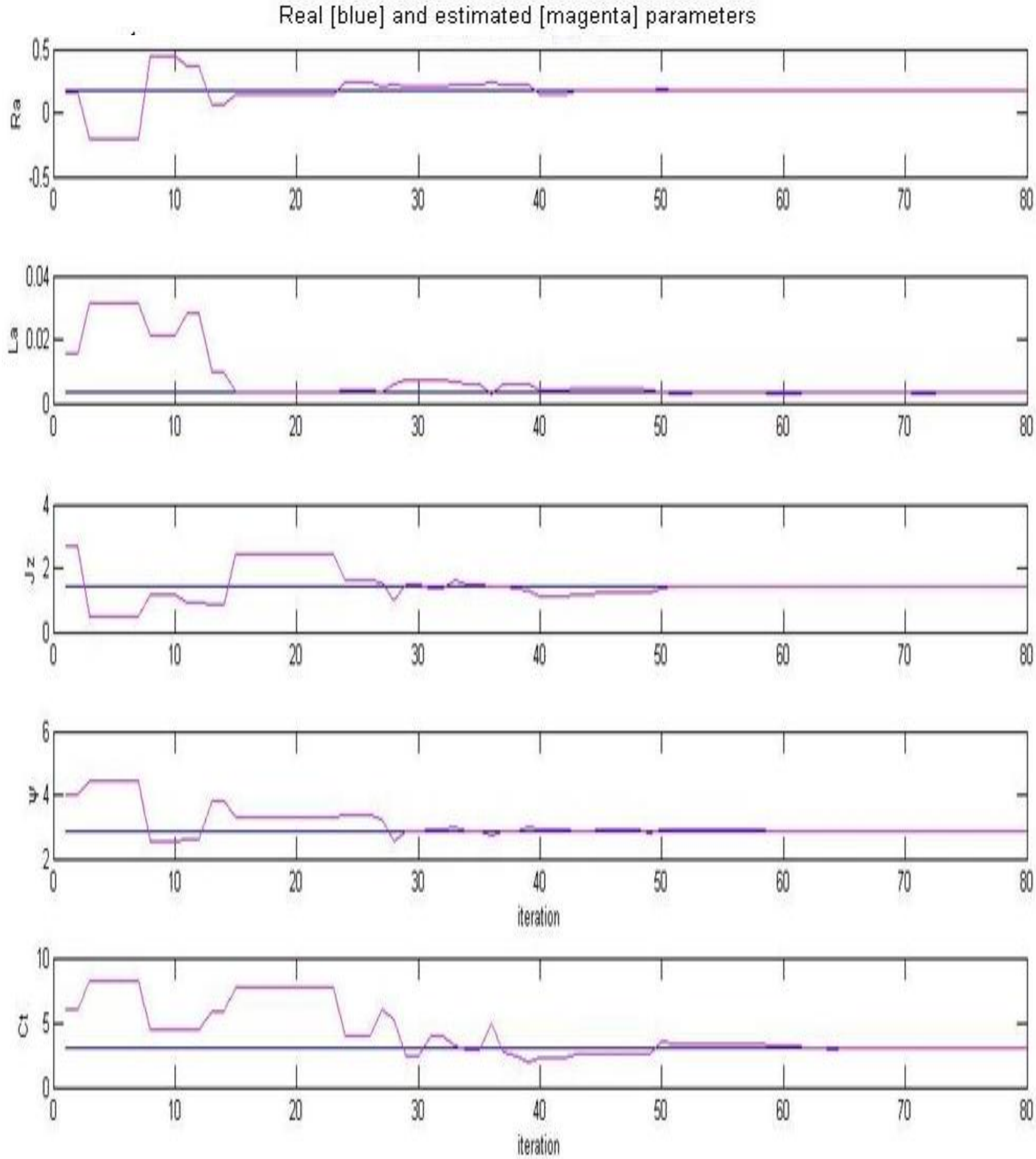

Figure 4.11 Optimization results for the bearing fault using M-PSO

The outcomes are compared in the below table 4.4 with the graphical representation Figure 4.12.

Table 4.4 Percentage error using PSO and MPSO for bearing fault for k = 1

Percentage of error					
Optimization	**Armature circuit resistance [Ohm]**	**Armature circuit inductance**	**Moment of inertia [kg*m^2]**	**Flux**	**Viscous damping coefficient [Nm/rad/sec]**
PSO	0.55714%	-0.5006%	- 0.01299%	-0.16046%	-0..00576%
MPSO	0.34153%	-3.6006%	0.7030%	-0.62334%	-0.93669%

The above trend firmly establishes the subsequent percentage of errors arising through the PSO and MPSO techniques till 80 iterations. The percentage of error is gradually reducing from 1st iteration to 80th iteration. The value of calculation errors must be considered in the context of peak of the abnormal parameters to the gradual optimized parameter and it would be unreasonable to expect that the percentage error will reduce to zero even with a large number of iterations.

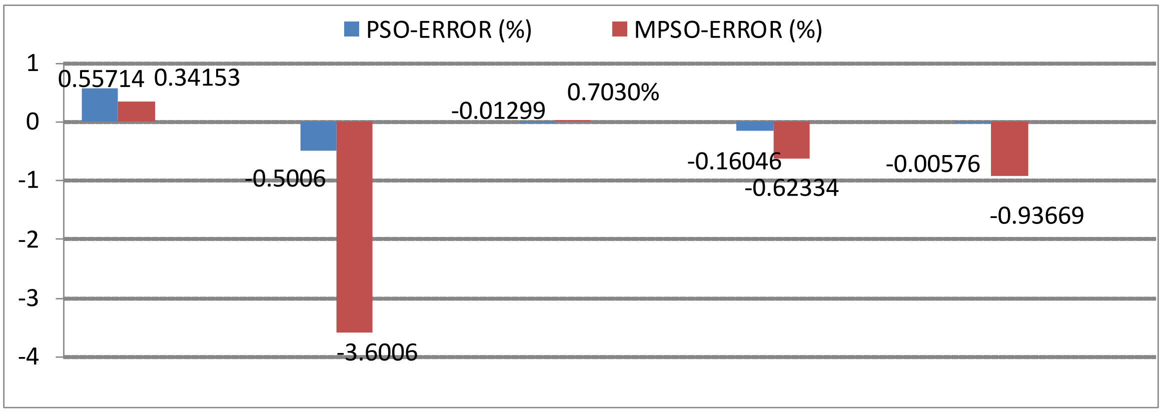

Figure 4.12 Graphical percentage errors in PSO and MPSO

It is clear from the optimization results that comparatively the PSO technique optimizes the result more rapidly with less percentage of error in bearing fault.

4.5 Summary

In order to accomplish a dynamic system health monitoring and fault diagnosis, most important task is the necessity to get enough consistent quality information from the system. A new technique for bearing fault identification is presented. Bearing faults could be obtained effortlessly in frequencies which are adapted with the essential frequency of the supply. Causes of bearing faults and defects are also explained as well. To monitor the motor status, the section emphasized techniques including fault detection and diagnosis as increasingly essential since prior identification of the defect lessens maintenance cost and motor outage time.

Chapter 5

Detection and Performance of air gap eccentricity

5.1 Introduction

Air gap eccentricity is considered as one of the widespread fault taking place in the induction motor. This kind of fault results in uneven air gaps amid the stator and rotor that has a bad effect on the output rotation correctness of the motor. If this kind of defect is not resolved originally, it would impact the rotor–stator rub and accordingly defect of the whole motor. Machine eccentricity is the provision of imbalanced air-gap which subsists between the stator and rotor. Once eccentricity becomes large, the consequential distorted radial forces also referred to as Unbalanced Magnetic Pull (UMP) could result in stator to rotor rub, and this could cause the impairment of the stator and rotor. The static and the dynamic air gap eccentricity are two different kinds of air-gap eccentricity.

5.2 Air-Gap Eccentricity Faults

Because of its simple construction and cheap maintenance and repair, the induction motor is the most commonly used motor in the industry. Static, dynamic or mixed eccentricities are three kinds of eccentricity. Also, there are basically three axes are in practice, which include rotor (O_r), stator axis (O_s) and rotor rotation axis (O_w) in an induction motor that is consistent with one another in standard condition. If eccentricity subsists then there is a disruption of any of the axis from the rest of other two axes or displacement of every axis. Eccentricity causes the imbalanced air-gap length alongside the stator to rotor limits. This imbalanced air-gap length might either be static or dynamic based on the kind of eccentricity. Three different types of eccentricity are given in Figure 5.1. The adverse vibrations are created in the stator windings as a result of radial magnetic pressures produced by eccentricity. The worst takes place when eccentricity affects rotor to stator rub that eternally impairs stator core and rotor cage [170]. [41] reported some unfavorable effects on the components of the induction motor caused by eccentricity include: increased power losses, owing to which efficiency reduces; the overall average torque reduces; differences in speed and torque goes high.

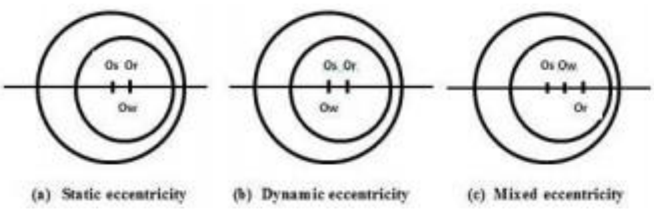

Figure 5.1 Different eccentricity types: (a) static, (b) dynamic and (c) mixed

The mainstream of the defects in three-phase induction motors have correlation with air- gap eccentricity that is the setting of the uneven air-gap amid the stator and the rotor. This fault could rise from large number of sources for example inaccurate bearing positioning at the time of assembly, damaged bearings, a shaft diversion, heavy load, etc. Generally, there are two types of air-gap eccentricity, which include radial and axial. All of them could be static or dynamic eccentricity as a matter of fact both static and dynamic eccentricities are likely to co-exist. An intrinsic range of static eccentricity subsists even in recently manufactured machines on account of manufacturing and assembly technique. This instigates a steady UMP in one direction. With application, this might result in bent rotor shaft, bearing corrosion etc. This might cause certain degree of dynamic eccentricity. [171] reported that if not detected early, these effects might increase into stator to rotor hub resulting in a main breakdown of the motor.

In the static eccentricity, the rotor is likely to dislocate from the stator center and the rotor revolves in its own center. Whereas, in the dynamic eccentricity, the rotor is as well dislocated from the stator center and the rotor revolves in the axis of the stator center. In the majority of cases, the static eccentricity and dynamic eccentricity concurrently take place. In that condition, the center of the stator and as well the rotor and the rotation axis are dislocated relating to one another [171] [172]. To identify the eccentricity fault, various kinds of techniques are employed, for example the monitoring of magnetic flux and vibration [173]. Though, as a result of the increased cost and complicated installation of sensors, the above mentioned techniques are comparatively less suggested. On the other hand, in recent period, motor current signature analysis (MCSA) is broadly employed to recognize the defect in the motors, since the stator current signal is relatively simple to obtain and do not require further intricate and high-priced sensors. The wavelet packet decomposition (WPD) has also been in practice to find the eccentricity fault and differentiated from one another in steady-state operating conditions. In addition to that, [174] pointed out that a time-domain technique known as Prony's technique is largely recommended for diagnosis of the air gap eccentricity with increased accurateness only using a 10-ms dataset.

Rotor eccentricity could emerge from various sources. For instance, even with severe manufacturing lenience, there is always, to a certain extent, a non-uniform air-gap in a motor. The better the tolerance, the lesser the overall manufacturing cost. Conversely, the overall lenience influences the performance of the motor and lessens the effectiveness. For motors with small air-gaps, the non-uniformity leads to imbalanced magnetic pull, and intensifies the extent of the harmonics creates further harmonics in the air-gap field. As machine air-gaps are generally narrow to certain extent, mechanical corrosion of the bearings could as well result in dislocation of the rotor from the axis of the stator bore. Eccentric operation of induction motors could give rise to an adequate intensification in the imbalanced magnetic pull to cause stator-rotor connection, which might give rise to critical impairment to both of them. Even at levels that are inadequate to create such a communication there might be an undesirable growth in vibration and as well subsequent noise emission. In order to inhibit the stator-rotor communication, because of variation of air-gap necessitates monitoring technique for the online identification of this difference. [175] pointed out that as air-gap flux density elements generate corresponding current elements in the stator windings, the current spectrum monitor the air-gap eccentricity and also health monitoring of induction motors.

In terms of air-gap eccentricity, static eccentricity is referred to as an inactive minimum air-gap, which could be produced by stator core non-circularity or inappropriate place of the rotor or stator at the organization stage. On the place of least air-gap there is an unstable magnetic pull that intends to redirect the rotor therefore intensifying the amount of air-gap eccentricity. Of these, dynamic eccentricity is referred to as a revolving minimum air-gap. The appearances of air-gap eccentricity create distinctive spectral systems and could be found out in the current spectrum. [176] exhibited that MCSA could efficiently eccentricity and various high resistance defects.

5.3 Air-Gap Eccentricity and Diagnostic Techniques

Condition monitoring of Induction motor is the continuous assessment of performance and health of the machine throughout its useful operating life and diagnosing fault at their very inception. By condition monitoring, we simply mean that monitoring the overall parameters of the induction motor when it is running on its full load capacity through the effective measurement methods in order that the motor‘s life and its effectiveness grows. [177] pointed out that in health monitoring there are two most significant elements one is the identification of defect through some competent and inclusive methods and the second one is the stage to diminish that effect that is reducing the efficiency of the induction motor, as it is not possible to eradicate the error that is already occurred to a large extent.

Condition monitoring has remarkable importance in the business context on account of the following reasons: increased machine accessibility and dependability, improved operating effectiveness and risk management, lessened maintenance costs and better safety. The condition monitoring is a non-invasive method of analysis that is the analysis is made farther than the induction motor. It is considered essential to detect and then categorize various types of defect modes which could take place within a motor system. Recurrently various kinds of sensors are used at various positions to obtain essential signals from motor. [178] examined various techniques including signal processing techniques such as Fast Fourier Transform (FFT), Time-Frequency methods such as Short Time Fourier Transform (STFT), Wavelet Transform (WT) and artificial intelligence techniques and fuzzy logic, that entails making conclusions on the basis of classifying signals into a sequence of bands instead of simply as strong or defective on the basis of a single threshold.

Air gap eccentricity is common rotor defect taking place in induction machines. This defect causes the uncertainties of vibration and noise. The air-gap eccentricity engenders difference in the air-gap flux density which generates noticeable variations in the vibration signal. Fault identification techniques are blend of feature extraction tool FFT, and the MCSA has been employed to obtain the stator short circuit defect. Static eccentricity is a steady drag in one direction that creates unbalanced magnetic pull (UMP). It is very much difficult to detect unless special equipment used [25, 97]. A dynamic eccentricity on the other hand produces a UMP that rotates at the rotational speed of the motor and acts directly on the rotor. This makes the UMP in a dynamic eccentricity easier to detect by vibration or current monitoring. Actually, static and dynamic eccentricities are likely to synchronize. Ideal centric circumstances could never be hypothesized. [180] stated that consequently, an essentially grade of eccentricity is evocatively implied for any authentic motor. All kind of motor defects creates the sidebands at particular frequencies in the air-gap torque.

At present the commercially accessible techniques for identifying rotor bar faults of induction motors are on the basis of different classifications of sidebands of a line current. [181] proposes a new technique for identifying not just the rotor faults but as well the stator shorted coils. Air-gap torque is the force created by the flux connections and the currents of a revolving motor. Air-gap torque could be assessed whilst the machine is running. Noise monitoring could be carried out by assessing and examining the acoustic noise spectrum from the motors. No down-time is essential for its assessment. Acoustic noise from air-gap eccentricity is effective to identify the defects of the induction motor. [181] has recommended noise signature for analyzing air gap eccentricity fault.

Condition monitoring and fault analysis techniques are mainly executed by examining the consequential anomalies in machine current, voltage and leakage flux. Other methods, such as observing the core temperature and bearing vibration level have been particularized to diagnose defect conditions for example insulation faults and lubrication oil and bearing faults. The least radial air-gap length is set up in space for static air-gap eccentricity. On the other hand, the center of rotor and the rotation are not likely to resemble for dynamic eccentricity. In such type of case, the position of minimum air gap is not set in space however rotates with the rotor. As specified by [103] a flawed location of the rotor or stator in the commissioning stage might cause static eccentricity. It might as well be engendered by stator core ovality. A foundation of dynamic eccentricity could be due to curved shaft, bearing weakening, or mechanical characters at essential speeds.

In recent times, a motor diagnosis technique is generally employed in industries, which are referred to as time-based maintenance (TBM). The TBM is protection carried out on equipment on the basis of calendar schedules. This refers to that the schedules will be significant for regular maintenance. Though, the TBM might cause over maintenance in order to inhibit substantial waste of manpower and resources. In contemporary environment, flourishing growths in the sensor, transmission, and information processing sectors have progressively made the real-time online-monitoring of motors an actual possibility. The most recent development in motor maintenance is therefore condition-based maintenance (CBM) that is efficient in accident avoidance. CBM as well facilitates motors to continue to be reliable right through their service time [182]. Thus, as pointed out by [183] it is essentially significant to establish a condition-monitoring system with fault diagnostic techniques employing a vibration–electrical hybrid technique for induction motors on the basis of CBM.

Contemporary measurement techniques along with highly developed computerized information process and acquisition exhibit new means in the field of induction motors monitoring by the application of spectral analysis of operational process parameters. Time-domain measurement with characteristic values to define variations by trend-setting, spectrum analysis to classify trends of frequencies, amplitude relations to find periodical elements of spectra is employed as measurement tools. In various settings, vibration monitoring techniques have been used for initial fault identification. Though, stator current monitoring is identified to give the similar indication without demanding access to the motor. Wavelet technique is also considered as one important technique for identifying fault diagnosis of induction motor. The benefits of using wavelet techniques for fault diagnosis of motors are progressively increasing as these techniques facilitate to carry out stator current signal analysis in transients. The wavelet technique could be employed for a localized assessment in the time-scale domain. It is subsequently an effective tool for health monitoring and fault diagnosis. Particularly, the pre-determined threshold systems for consistent diagnosis of electrical defects intervention in motor faults employing MCSA can be employed to assess the fault criticality, but these threshold systems likely to find adequately strong defect signatures to inhibit noise interference. Thus, as pointed out by [184] the system cannot be used to analyze small defect signatures related to motor mechanical defects in no-load conditions.

5.4 Experimental Setup and Optimization

5.4.1 Experimental setup

The effect of air-gap spectrum is likely to produce unique spectrum, which is identified during the analysis

$$f_{ag} = \{ (k_{rt}R \pm k_d)(1-s) \pm k_{ws} \} f_s \qquad (8)$$

Where f_{ag} = frequency component due to air gap eccentricity

k_{rt} = Any Integer 0,1,2,3,….

R = Number of rotor bars

k_d = Eccentricity order number , $k_d = 0$ (Static eccentricity)

$k_d = 1,2,3\ldots$ (Dynamic Eccentricity)

p = No. of poles i.e. half the no. of poles = P/2

s = Slip ratio

k_{ws} = Order no. of stator MMF time harmonic

f_s = Supply frequency

A static air-gap eccentricity is presented in the induction motor by machining the housing of the motor and rotor then a grub screw is being inserted in the housing in order to shift the rotor’s symmetry. Figure 5.1 (a) and 5.1 (b) depicts the eccentricity method. A balance of 0.1mm is produced from in a total of 0.4mm air-gap. In consequence, 25% static eccentricity is obtained in the setup given by figure 5.2

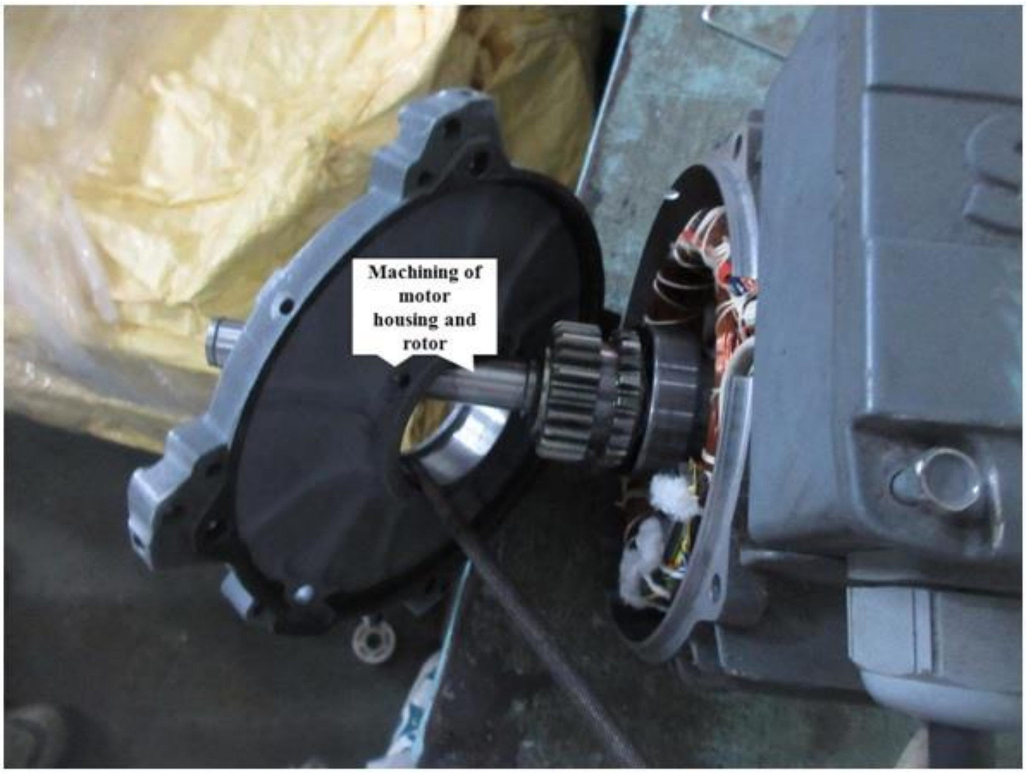

Figure 5.2 Housing and rotor of motor to obtain eccentricity

The expected fault frequencies are given in table 5.1

Table 5.1 Static 25% Air gap eccentricity fault condition expected frequency

Load condition	**Speed**	**Slip**	**k_{ws} = ±1**	
			LSB (Hz)	**USB (Hz)**
No Load	1395	0.07	787Hz	887Hz

The findings of a SEW-EuroDrive Motor are hereby represented by figure 5.3. The yellow and the white color signal denotes the time-domain and frequency-domain signal of the healthy Induction motor respectively. The Centre Frequency denotes, f = 50Hz. The slip sidebands are comparatively less obvious in terms of the healthy motor.

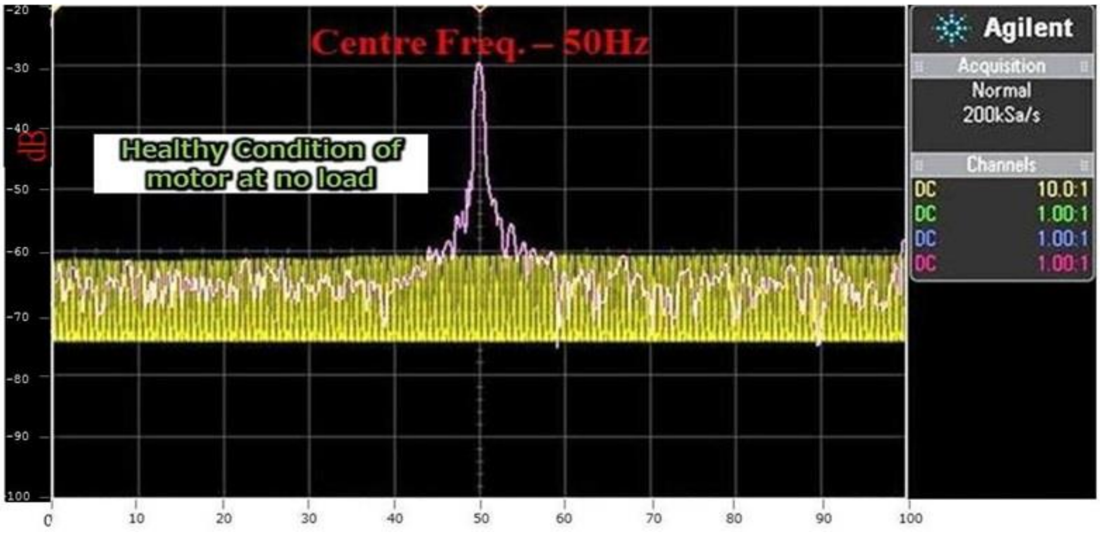

Figure 5.3 Spectrum for a SEW-EuroDrive Motor in Healthy condition at no load

Figure 5.4 represents the static air gap eccentricity fault, in which the resulting fault frequency is at 784Hz with amplitude of 145dB.

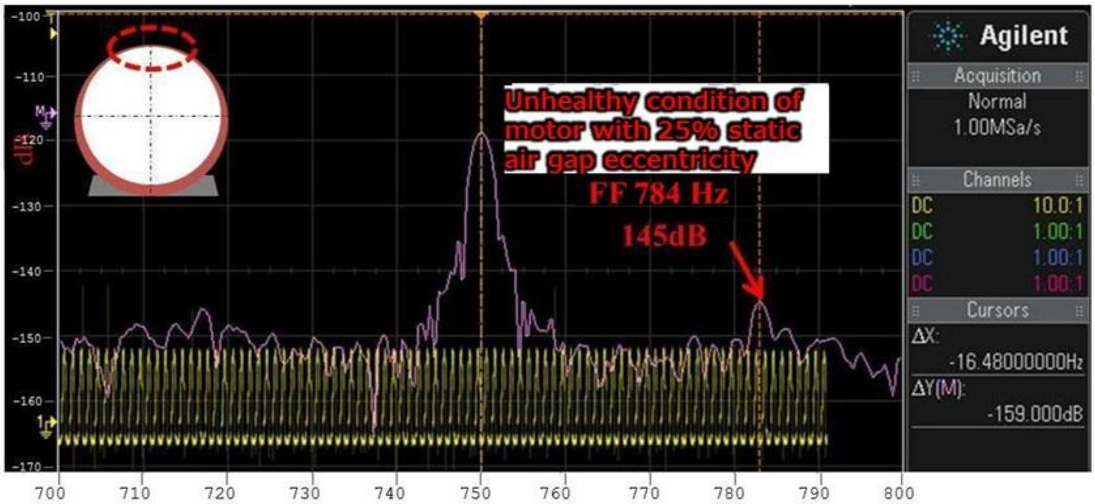

Figure 5.4 Spectrum for a SEW-Euro Drive Motor in Unhealthy condition at no load with k_{ws} = 1

Both Particle Swarm Optimization (PSO) and Modified Particle Swarm improvement (MPSO) has been employed for parameter approximation specifically to optimize the condition back to healthy one and also for the purpose of comparative analysis. The experiments have been completed on 1.5kw and 440V, SEW EURODRIVE induction motor and parameter assessment have been through MATLAB/Simulink algorithms.

For the analysis of performance, the same hardware setup has been used; thereafter the fault frequencies which are related to the 25% static air-gap eccentricity fault [LSB = 787Hz and USB = 887Hz] have been used as reference range frequency to optimize the faulty behavior of the induction motor.

5.4.2 Optimization

As explained in chapter 4 under section 4.4.2, the same methodology has been deployed. After applying the PSO and MPSO for parameters approximation, the results are compiled through algorithm through MATLAB/SIMULINK.

Test motor parameters

Ua	=	Rated Armature Voltage [V],420V
Mm	=	Rated torque [Nm],20Nm
I	=	Rated Current [A],3A
Ra	=	Armature Circuit Resistance [Ohm], 0.177ohm
La	=	Armature Circuit Inductance [H],0.00334H
N	=	Rated speed [RPM],1395
W	=	N*pi/30; Rated speed [rad/sec]
Jz	=	1.4; Moment of inertia [kg*m^2]
psi	=	(Ua-Ra*I)/W; Flux
Ct	=	3; Viscous Damping Coefficient [Nm/rad/sec]
LSB	=	787Hz
USB	=	887Hz

Now the optimization is done with the application of PSO and MPSO and later air gap eccentricity fault is simulated. Figure 5.5 shows the behavior in faulty condition obtained in PSO whereas Figure 5.6 represents the defective condition obtained in MPSO.

```
(1/80) Motor vs. ident:  0.177 vs. 0.518, 0.00334 vs. 0.0018,1.4 vs.
3.79,2.87 vs. 3.9, 3 vs. 3.78
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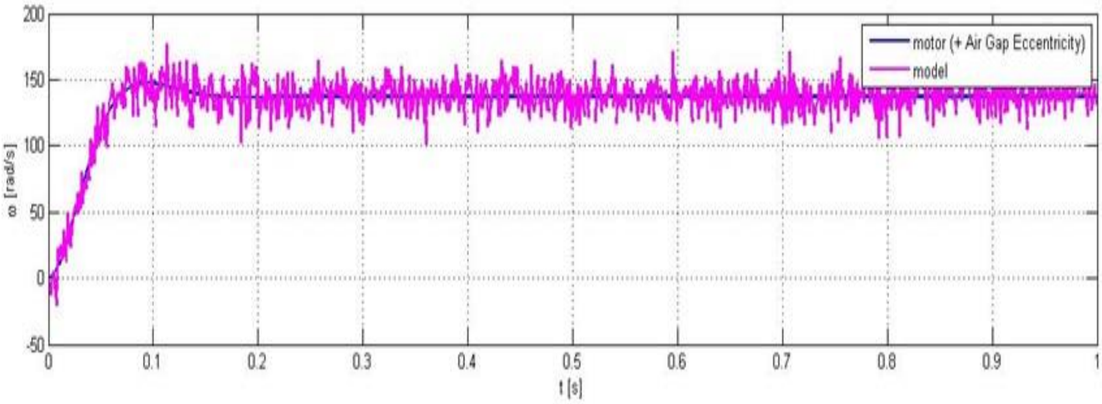

Figure 5.5 PSO Technique for a SEW-Euro Drive Motor in Unhealthy condition at no load with 25% air gap eccentricity

```
(1/80) Motor vs. ident:  0.177 vs. 0.584, 0.00334 vs. 0.016, 1.4 vs.
3.05, 2.87 vs. 4.76, 3 vs. 7.16
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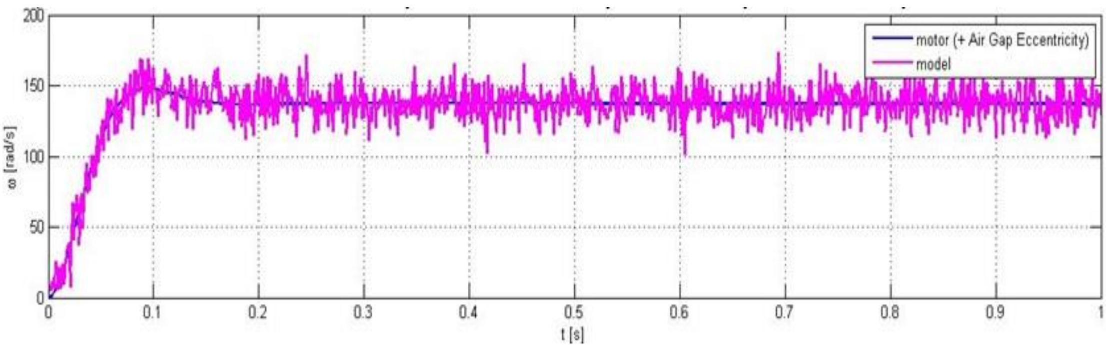

Figure 5.6 M-PSO Technique for a SEW-EuroDrive Motor in Unhealthy condition at no load with 25% air gap eccentricity

The below figures 5.7 and 5.8 shows the parameter convergence till 80 iterations using PSO and MPSO respectively.

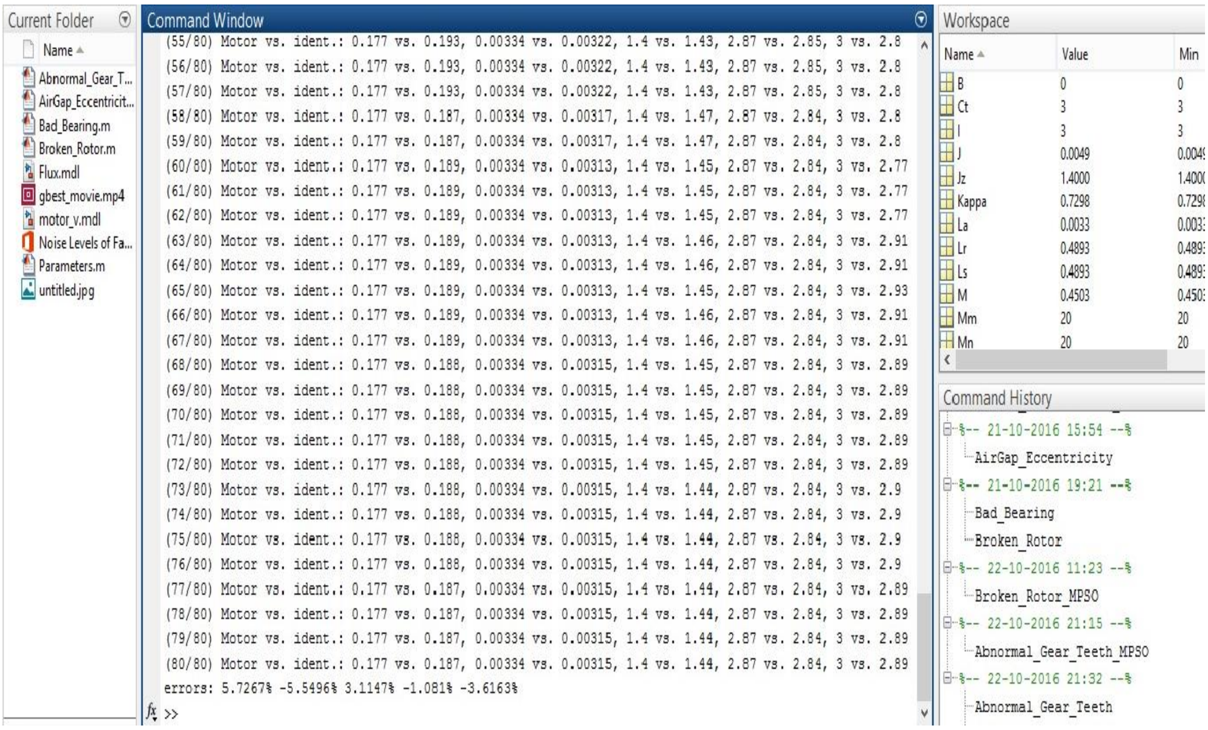

Figure 5.7 Error Convergence using Particle Swarm Optimization

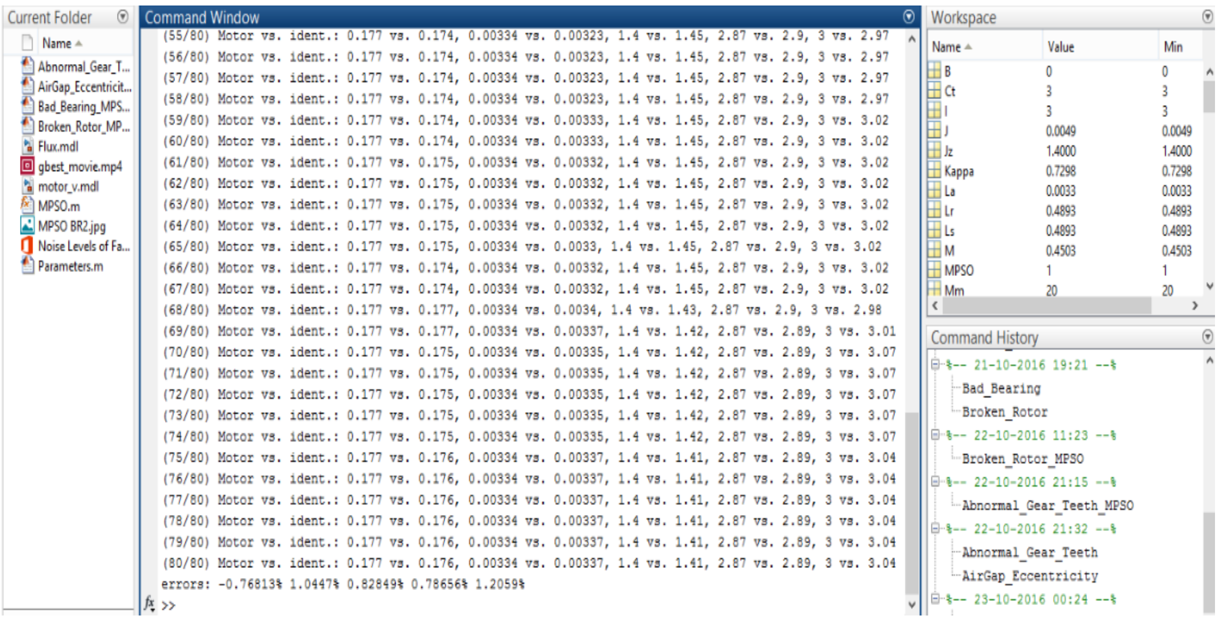

Figure 5.8 Error Convergence using Modified Particle Swarm Optimization

Besides, a comparative analysis between the outcomes of the MPSO and PSO has been done in order to authenticate the effectiveness of the proposed technique.

Figures 5.9 and 5.10 represent all the parameters optimization results with PSO and MPSO respectively.

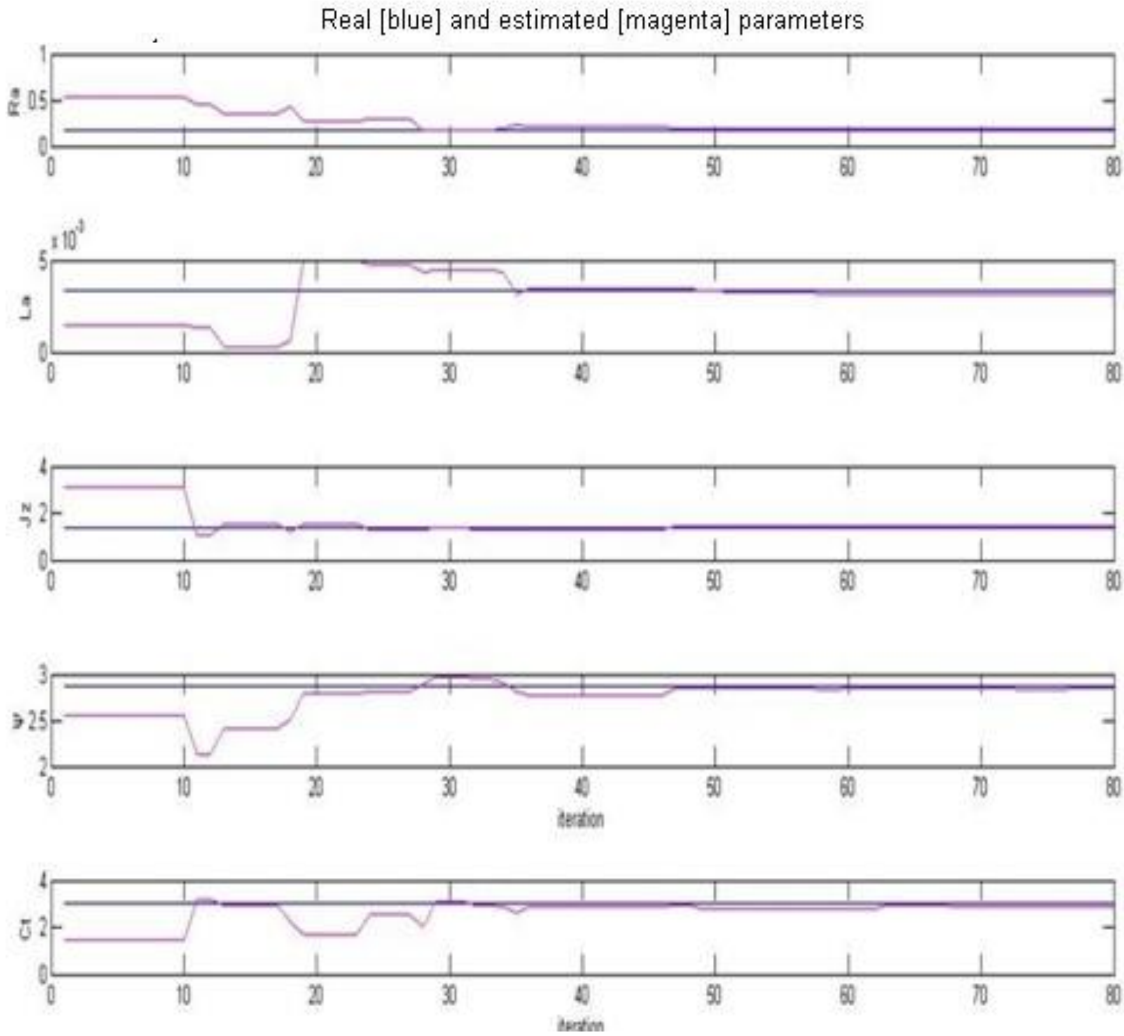

Figure 5.9 Optimization results for the air gap eccentricity using PSO

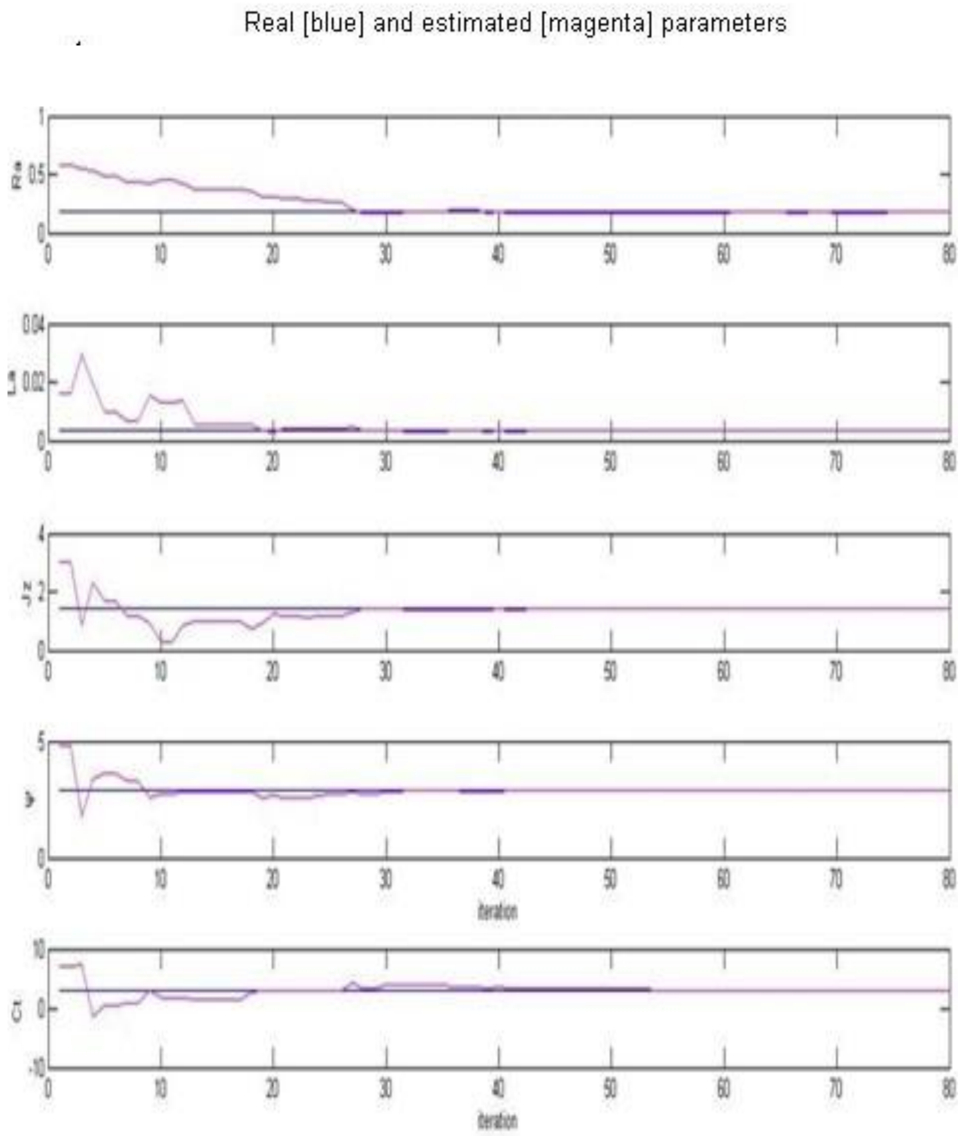

Figure 5.10 Optimization results for the air gap eccentricity using M-PSO

Comparison has been done on the optimization outcomes based on percentage of error in order to put forward the better optimization methods. The comparison results are given in the below table 5.2 with the graphical representation Figure 5.11.

Table 5.2 Percentage error using PSO and MPSO for air gap eccentricity fault

Percentage of error					
Optimization	**Armature circuit resistance [Ohm]**	**Armature circuit inductance**	**Moment of inertia [kg*m^2]**	**Flux**	**Viscous damping coefficient [Nm/rad/sec]**
PSO	5.7267%	-5.5496%	3.1147%	-1.081%	-3.6163%
MPSO	-0.76813%	1.0447%	0.82849%	0.78656%	1.2059%

From the table it is evident that MPSO optimized with lesser percentage of error in case of 25% static air-gap eccentricity among all the parameter estimation. The two different optimization techniques are also graphically compared.

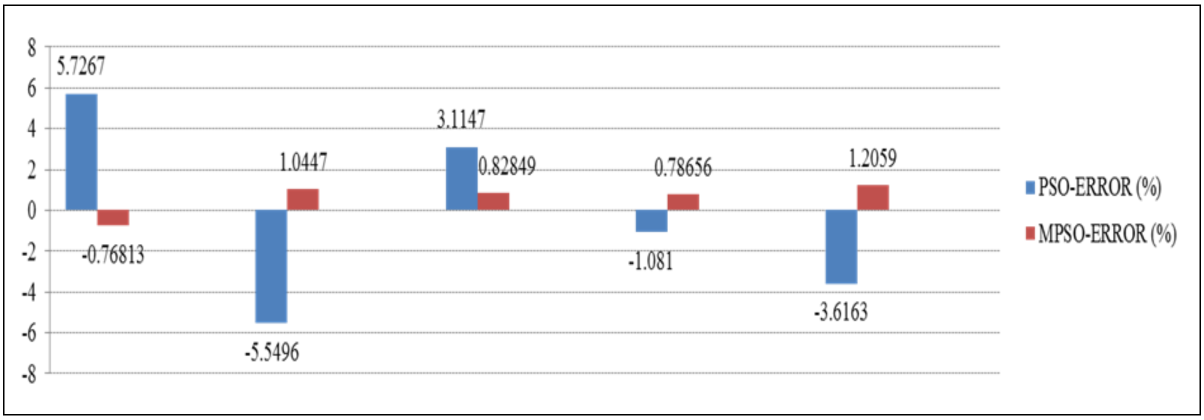

Figure 5.11 Graphical percentage errors in PSO and MPSO

The above trend indicates the subsequent percentage of errors arising through the PSO and MPSO techniques till 80 iterations. The percentage of error is gradually reducing from 1st iteration to 80th iteration. The value of calculation errors must be considered in the context of peak of the abnormal parameters to the gradual optimized parameter and it would be unreasonable to expect that the percentage error will reduce to zero even with a large number of iterations.

5.5 Summary

This makes an effort to assess the recent progressions in induction motor fault analysis. Several methods and algorithms have also been examined and the appropriateness of an exact technique for an individual fault analysis has been highlighted in this chapter. Primarily, is the fault identification and second, is the condition monitoring and fault diagnosis of induction motors. There are various conclusions and suggestions that could be drawn from this chapter, such as diagnostic techniques that are used for air-gap eccentricity faults and role of condition monitoring for such faults.

Chapter 6

Diagnosis and Performance of Broken rotor bar fault

6.1 Introduction

The induction motors are mostly used in all types of sectors all around the globe. Although induction motors are consistent, they are vulnerable to several kinds of faults. There are several approaches feasible for fault detection in induction motor but most of the approaches needs costly sensor or specialized components whereas current supervision out of all does not need extra sensors. The MCSA (Motor Current Signature Analysis) employs the present motor spectrum for locating fault frequency features. MATLAB software is employed to identify the faults of broken rotor bar of induction motor. The Particle Swarm Optimization and Modified Particle Swarm optimization is used for diagnosis of broken rotor bar fault in induction motor. The optimization results of both the methods are discussed and compared and the final results are obtained.

6.2 Broken Rotor Bar

The broken rotor bar at the initiation does not generate severe damage to induction motor at the later stage it can produce severe harm to induction motor. This can cause mechanical destruction to winding insulation and thus the failure of winding occurs. Therefore, an early prediction is very essential to avoid losses in production. The BRB can be affected by two reasons: 1) imbalance or pulsating mechanical loads can subject the rotor cage to greater mechanical stress; and 2) imperfection at manufacturing time of rotor cage. Different techniques of signal processing in integration with developed computerized data acquisition and data processing reveals new approaches for the analysis of broken rotor bar for example wavelet transform, Fast Fourier Transform and Short Time Fourier Transform etc.

6.3 Effects of Broken Rotor Bar in Induction Motor

It has mentioned [185] that the condition of broken rotor bar initiates with fracture at junction between the end ring and rotor bar as an outcome of mechanical and thermal stresses. These stresses are much essential when initiating motors with greater inertia loads. The fractured bar bending due to alterations in temperature causes the bar to crack. When one bar cracks the parallel bar undertake currents larger than their values of design causing much destruction if the condition of broken bar is not predicted properly. The inter-bar currents that exist because of the effect of broken bar influence the fault evolution in rotor causing destruction in rotor core laminations.

The area of research in [186] has mentioned some of the reasons where rotor bars can be broken partially or wholly. The reasons are thermal effect loss or over heat resulting from sparks, unbalanced magnetic attractions, electromagnetic forces, magnetic impacts stemming from vibration and noise, the impacts stemming from defects of manufacturing, stemming effects from torque, revolution and centrifuge, chemical impacts or environmental impacts causing rotor material wear away because of losses in sheet, moisture, fatigued mechanisms and the mechanical stress existing as an outcome of bearing faults.

It has been mentioned [187] that broken rotor bars can be a serious issue with induction motors due to arduous duty cycles. Although, BRB do not cause induction motor to fail but there can be secondary impacts. Severely fault process outcome in broken parts of bar hitting the stator core or end winding of a high voltage motor at greater velocity. This can heavily impact the mechanical destruction to insulation and a consequential failure of winding may follow resulting in expensive repair and production losses.

This has been stated [188] that the induction motor's squirrel cage comprises of rotor bars which are short circuited with the use of end rings. A broken bar can be wholly or partially cracked from the end rings. Such bars could crack or break because of built up defects, frequent initiation at rated voltage, mechanical stress or thermal stresses caused by metal fatigue and bearing faults. A broken rotor bar of induction causes huge effects. A well familiar cause of a broken bar is the development of so known sideband components. These sidebands are predicted to appear on the right and left side of fundamental frequency component in stator current power spectrum of stator current. The general reason for the occurrence of right sideband component is due to consequent ripple speed caused by resulting pulsations of torque whereas the component of lower side band in stator currents power spectrum is magnetic and electrical asymmetric in induction motor's rotor cage.

Broken rotor bars cause instant failures specifically in wide multi pole gradual speed machines [189]. There are adequate BRB so that the motor could not initiate because it will most probably be unable to create sufficient accelerating torque. The broken bars can root sparking i.e., a genuine concern in severe places. IF more than one rotor bar is cracked the robust bars are enforced to provide additional current prompting core harm in rotor from continual raised temperatures in the broken bar region. The expansion of non-uniform bar may exist due to huge air pockets in die cast rotor windings made up of aluminum alloy prompting to bending rotor and asymmetry that roots greater levels of vibration from untimely bearing wear. The broken rotor bars can exist short on space as the rotor speed is high because of the force across stator winding and centrifugal force leading a calamitous failure in motor. The static and dynamic rotor asymmetry could make the rotor rub against the stator winding causing destruction to rotor core and a severe fault.

6.4 Diagnosis of Broken Rotor Bar Fault using Fast Fourier Transform

A stringent quality control is used in the process of production and the better condition of electrical machines can be acquired by using diagnostics [190]. There are several approaches that can be employed for electrical machines diagnostics. This study initiates with a novel automated practical implementation for noncontiguous broken rotor bar diagnosis and detection in induction motors. In this study a process for diagnosis and detection of BRB side is based on spectral examination through FFT (fast Fourier transform) and spectral response classification based on fuzzy controlled identifier. A fuzzy identifier will be used to recognize the broken bar numbers. [191] have stated in their study that induction machines are the major hub of several industrial processes due to its reliability and robustness. The induction motors condition monitoring is the method of processing motor behavior before essential alteration which leads to evolving fault. The voltage signals and/or motor currents are often modulated by the condition of fault inside the motor. Using various mathematical and signal processing technologies these signals can be examined, interpreted and motor faults can be recognized. Motor Current Signature Analysis Technique using Fast Fourier transform method is used in this study to recognize the fault of BRB of induction motor under various conditions of loading. [192] presented a fault diagnosis of induction motor at closed loop and the fault considered in the machine is the adjacent broken rotor bars. The control technique used is the vector control to secure the regulation of speed and compensate the fault impact and to assure the machine's continuity of service. Many mechanical and electrical quantities are examined using fast Fourier transform for the prediction of fault of rotor bar. The Fast Fourier Transform technique examination on control signals of closed loop provides clear data about the occurrence of fault where the quadratic component provides a benefit and becomes a proper feature for detection of fault. [193] study reviews various induction motor type rotor fault detection. Preventive maintenance is one of the major concerns in modern sector where the detection of failure on motor enhances the machinery lifecycle. BRB are the most similar failures in induction motors. The scheme of Asui table monitoring helps to decline failure propagation or restricts its escalation to serious degrees and thus hinders unplanned downtimes that cause financial income and production loss. This study discusses various fault detection methods namely fuzzy logic, fast Fourier transform and artificial neural network-based method. [194] presents the classification and detection of BRB fault of induction motor using ANN and fuzzy logic. The fast Fourier transform is used for transforming the actual waveform stator current which is time domain to stator current signal which is based on frequency domain that is mentioned as motor current signature examination for gathering important information for sending into fuzzy logic and ANN.

6.5 Diagnosis of Broken Rotor Bar Fault using Short Time Fourier Transform

The study of [195] has contributed to the developing use of IM in electrical systems. The induction machines use is mainly due to their ratio of power and weight, robustness and their reduced manufacture cost. Still different defects may occur in electrical machines. The PSD (Power Spectral Density) based on FT (Fourier Transform) is employed as a process of examination for several years for its reduced time of computing and simplicity. Additionally, this approach is based on the evaluation of Fourier transform; implicit denotes that the spectral signal properties are stationary. With the growth of different applications of speed, the spectral features of the stator current become non stationary and spectra are much greater in harmonics. To resolve these issues this study used a time frequency domain named STFT (Short Time Fourier Transform) providing additional data on alterations of frequencies with time in stator current signal case.

In the study of [196] induction motors particularly squirrel cage induction motors have an essential part in the field. Their rotor may be failed under stresses relying on their application and get unexpected condition of failure during the operation of motor. The growth in transformative techniques of digital signal processing have motivated authors to process much information in reduced amount of time. The most frequently used technologies for rotor faults detection are Short Time Fourier Transform and Fast Fourier Transform. The Short-Time Fourier Transform technology is capable to identify faults in transient conditions but faced the issue of frequency resolution. In this study the fault of BRB has been predicted by domain of time, frequency (Fast Fourier Transform) and time frequency (Wavelet Transform) technologies. [197] has stated in their research that monitoring systems for the detection of induction motor fault have been of huge concern for the sector in present years. Those based on examination of electric current supply are the most similar since the current signal offers similar data considering the condition of motor. The Fourier Transform is a familiar approach for carrying out this examination however it does not permit viewing the signal evolution through time. On the other side Short

Time Fourier Transform has ensured to be helpful for examining the evolution of signal frequency through time.

Unfortunately, the representation of frequency and time heavily relies on the size of used window and its resolution. In this study an approach based on functions of window and Short Time Fourier Transform is suggested for developing the time frequency representation resolution. The proposed method is used in the signal of electric current supplied to an induction motor developing the characteristic frequency components visualization of broken rotor bars. [198] has mentioned in their study that induction motors play an important part in the field of different industrial applications. Tough conditions of working and long-time service make induction motors become prone to a BRB that is one of the main effects of induction motor faults. The benefit of wide applicability and greater reliability in fault diagnosis and condition monitoring based on results of vibration signature analysis in an improved CMS (cyclic modulation spectrum) is one of the cyclic spectral analysis algorithms. Cyclic Modulation Spectrum is suggested in this study for the identification and detection of broken bar rotor faults in induction motors at an operation of steady state based on the analysis of vibration signature. The cyclic modulation spectrum application is based on STFT (Short Time Fourier Transform) and the developed Cyclic Modulation Spectrum method is attributed to optimization of Short Time Fourier Transform.

6.6 Diagnosis of Broken Rotor Bar Fault using Wavelet Transform

Wavelet Transform performance evaluations are executed under BRB fault diagnosis. In this study the current in stator phase was employed for wavelet analysis [199]. The stator current coefficients of DWT (Discrete Wavelet Transform) in a particular band of frequency are analyzed and derived. The wavelets sensitivities to signal faults are assessed and compared to choose the most optimal one. This method enhances the diagnosis and detection of BRB existence or even number of BRB under variation of load. [200] have mentioned in their study that the analysis of motor current signature has been used successfully for the diagnosis of fault in IM. However, this approach does not often accomplish better outcomes when the load torque or speed is not stable because this causes difference on the motor slip and the issues of FFT occur due to non-stationary signal. This study explains the impacts of BRB fault in stator current of IM performing under conditions of non-constant load. To accomplish this BRB fault is replicated in a lab and its impact on motor current has been studied. To resolve the BRB fault a new method based on wavelet transform is used in this study. [201] presents two diagnostic approaches for broken bars detection in induction motors with squirrel cage rotors namely wavelet method and fast Fourier transform. The fast Fourier transform approach performs predicting BRB when the motor performs under a load but if the machine is decoupled from mechanical load, the components of side band related with broken bars do not exist. The wavelet transform method is a strong tool of signal processing employed in power systems and other fields also. New wavelet-based methods of detection that are concentrated on the examination of startup current have been suggested for broken bars detection. The main purpose of this study is to predict the benefits of wavelet transform method compared to Fourier transform approach in detection of rotor failure of induction motors. [202] has mentioned in their study that the electric motors fault detection has been studied widely due to the significance of the devices at industrial level. This study presents the examination of various techniques of signal processing used for the detection of broken bar of 3 phase induction motors. Hilbert Transform, Fast Fourier Transform and Wavelet Transform are examined to acquire the features of motor current signal of faulty and healthy IM. The main benefits and barriers of every processing technology used for the detection of BRB of IM are discussed in this study. [203] shows various method of analysis with computerized acquisition and data processing and provide new areas in induction motor’s condition monitoring. The modern sector used mainly reliability and strategies of condition maintenance to decrease unexpected failures. These technologies may enhance the time between scheduled shutdowns for standard management and decrease operational and maintenance cost. This study mainly discusses the BRB fault detection and fault of air gap eccentricity by using MCSA (Motor Current Signature Analysis) method and Wavelet Analysis Method. These two methods are useful in real time tracking of different defects of motor and decide the severity of it which can be employed for rapid decision making. The research on faulty and healthy motor under various condition of speed is undertaken experimentally and the outcomes are examined using Fast Fourier Transform spectrum.

6.7 Various techniques used for detecting Broken Rotor Bar faults

As contributed by [204], it has been mentioned in their research that induction motor plays an essential part in industrial sector. However different faults can exist such as rotor failures and short circuits this study proposes an ANFIS (Adaptive Neural Fuzzy Inference System) based technique to classify and detect the BRB faults in a 3-phase induction motor. This classification and detection are based on the analysis of stator current signal.

The efficiency of using ANFIS technology to classify and detect the BRB faults of 3 phase induction motors is examined. The results of simulation clearly mention that the signature of stator current can be employed to identify squirrel cage rotor faults using Adaptive Neural Fuzzy Inference System. [205] has proposed a new technique for BRB diagnosis in induction motors at non-stationary state and reduced load. This technique is employed to resolve the issue from using classical signal processing technique Fast Fourier Transform by examination of stator current envelope. The proposed approach is based from using Hilbert Transform and Discrete Wavelet Transform. The Hilbert Transform is employed to retrieve the envelope of stator current. Then this signal is processed through discrete wavelet transform. [206] proposed an off the grid compressive sensing based approach to predict BRB fault in squirrel cage IM. To validate the approach a dynamic squirrel cage IM model is constructed using multi loop equivalent circuit to simulate motor current under conditions of fault. Then an off the grid compressive sensing algorithms are developed to retrieve the fault feature frequency from the simulated motor current by resolving an atomic rule minimization issue. Compared to other methods of fault detection through analysis of motor current signature the off the grid compressive sensing approach generates greater resolution in retrieving reduced magnitude fault frequency characteristic with 0.7 second measurements. [207] has described in their research that induction motors are employed in different industrial applications where consequent startups are needed. In those cases it is essential to use sophisticated methods of signal processing to follow the evolution of time of fault associated harmonics in the signal. In this study ZSC (zero sequence current) is examined using greater resolution spectral approach of MUSIC (multiple signal classification). The examination of zero sequence current signals has proven to have many benefits over the examination of single phase current waveform. The experimentation is carried out on a healthy motor, a motor with one BRB and a motor with two BRB. The results of analysis are fulfilled since the proposed method detects the BRB fault reliably both during steady and transient state operation of IM. [66] has mentioned in their study that as an outcome of developing machine abilities in modern manufacturing the machines performs continuously for several hours. Therefore, early detection of fault is needed to decrease the expense of maintenance and obviate greater cost and unplanned downtimes. The systems of fault diagnosis that offers pattern classification and feature extraction of the fault are capable to classify and detect the failures in machines. Most of similar works that mentions a process for rotor bar breakage detection have applied the analysis of motor current signal using discrete wavelet transform. In this study the most proper characteristics are retrieved from wavelet packet transform coefficients after current signal's Fourier Transform. Through integrating the strength pf both frequency and time scale domain analysis technologies a unified wavelet packet signature examination denotes the fault signature in special fault-oriented bands of frequency. The wavelet analysis integrated with a feed forward NN classifier offers an intelligent methodology for automatic identification of fault severity during motor runtime. The severity of faults is regarded as more than two BRB. The results have assured that the proposed approach is efficient for identifying fault of BRB in an induction motor and fault severity classification. [208] presents the BRB fault diagnosis and detection in IM. Indeed, the fault of BRB do not have a beginning impact it can lead IM to fail since there can be severe secondary impacts. A new fault diagnosis and detection method namely the TSA-fuzzy is proposed. This technique employs the residual current acquired by the TSA approach. In fact, this current develops to predict faults that cannot be predicted by examining stator current particularly in low load motor. The RMS of the load and residual current will be employed as inputs for block of fuzzy logic where the decision about the rotor state is made. The output shows the efficiency and reliability of the proposed method.

6.8 Experimental setup and Optimization

6.8.1 Experimental setup

A forwarding rotating magnetic field is generated in induction motor under perfect balanced condition at synchronous speed by the below given equation:

$$n_s = \frac{120 f_s}{p} \quad (9)$$

Where n_s indicates the synchronous speed, f_s indicates the frequency supply and p denotes the number of poles. The slip of the IM is generated by the below equation:

$$s = \frac{n_s - n_r}{n_s} \quad (10)$$

Where n_r is the speed of rotor. The upper side band and lower side band are mainly due to broken bars which are represented by the equation below:

$$f_{brb} = (1 \pm 2ks) f_s \quad (11)$$

Where f_{brb} is denoted as frequency of broken rotor bar, k denotes 1, 2, 3…. and f_s indicates the frequency of supply. The expected frequencies of fault are presented in the below table:

Table 6.1 Expected frequency of BRB fault with k values as 1, 2, 3

Load condition	**Speed**	**Slip**	**k=1**		**k=2**		**k=3**	
			LSB	**USB**	**LSB**	**USB**	**LSB**	**USB**
No Load	1395	0.07	43 Hz	57Hz	36Hz	64Hz	29Hz	61Hz

The SEW-Euro Drive motor results are shown in the below Figure 6.1

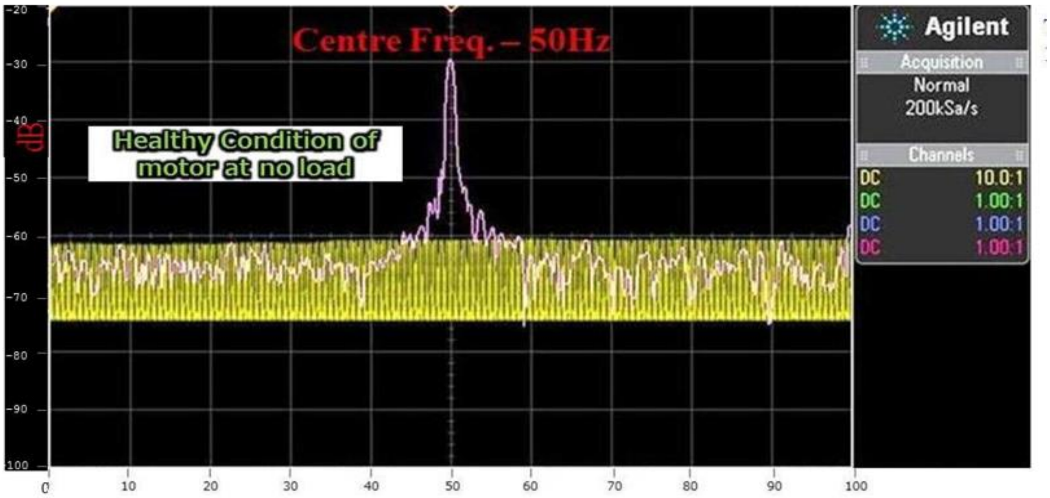

Figure 6.1 SEW EURO DRIVE Motor Spectrum in healthy condition at no broken rotor with no load

From the above figure the signal with yellow color indicates the signal of time domain and white color indicates the domain of frequency of healthy IM. The center frequency is denoted as f-50 hertz. The slip side ban ds are less viewed in healthy motor case. A BRB is made by destructing the rotor bar as shown in the below figure by reducing the assembly of rotor diagonally with 1.5-millimeter slot. The damage was carried out on four sides of the rotor. The below figure 6.2 shows the assembly of broken rotor bars:

Figure 6.2 Assembly of Broken Rotor Bar

An unhealthy broken rotor bar spectrum is presented in the below figure 6.3 which reveals that the frequencies of fault are existing at 53 hertz and 47 hertz as expected with 45 decibel and 48 decibels respectively:

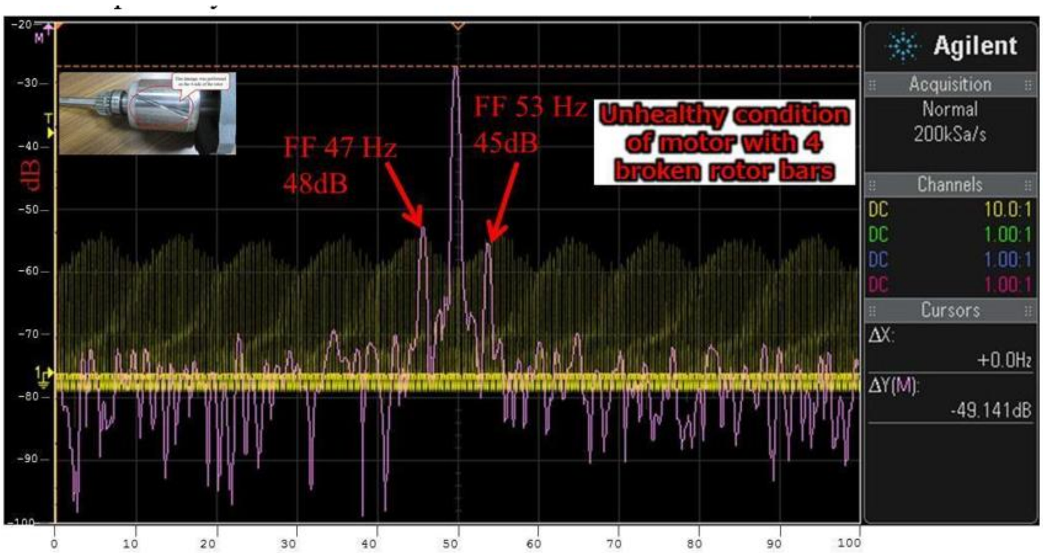

Figure 6.3 SEW EURO DRIVE Motor Spectrum in unhealthy condition with broken rotor

6.8.2 Optimization

The MPSO (Modified Particle Swarm Optimization) and PSO (Particle Swarm Optimization) are employed for approximation of parameter that is to optimize the condition back to healthy one and for comparative research. The experiments are finished on SEW EURODRIVE, 1.5 kilowatt, 440 volt IM and assessment of parameter is completed through algorithms of SIMULINK and MATLAB. For the purpose of optimization, the similar set up of hardware has been employed and then the frequencies of fault associated to BRB are considered as the range of reference to optimize the induction motor faulty behavior. The Modified Particle Swarm Optimization and Particle Swarm Optimization are applied on the initialized parameters of motor and the results are collected later through SIMULINK/MATLAB.

Parameters of Motor

Ua=Rated Armature Voltage [V], 420V

Mm=Rated torque [Nm],20Nm

I =Rated Current [A],3A

Ra = Armature Circuit Resistance [Ohm], 0.177ohm

La = Armature Circuit Inductance [H],0.00334H

N = Rated speed [RPM],1395

W = N*pi/30; Rated speed [rad/sec]

Jz = 1.4; Moment of inertia [kg*m^2]

psi = (Ua-Ra*I)/W;   Flux

Ct=3;   Viscous Damping Coefficient [Nm/rad/sec]

LSB = 47Hz

USB = 53Hz

The Modified Particle Swarm Optimization and Particle Swarm Optimization are applied for BRB fault. The below figure 6.4 shows the faulty condition behavior in Particle Swarm Optimization:

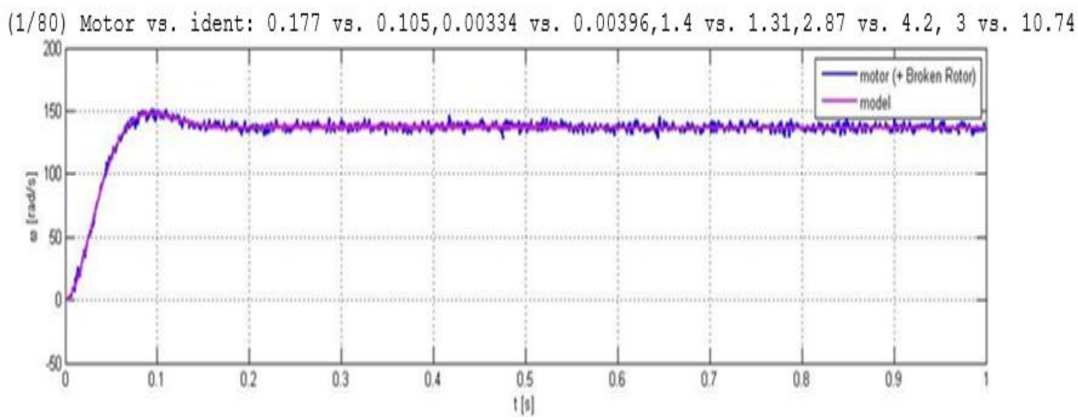

Figure 6.4 Particle Swarm Optimization Technique for SEW EuroDrive Motor in BRB unhealthy condition

Another figure 6.5 shows the Modified Particle Swarm Optimization in faulty condition:

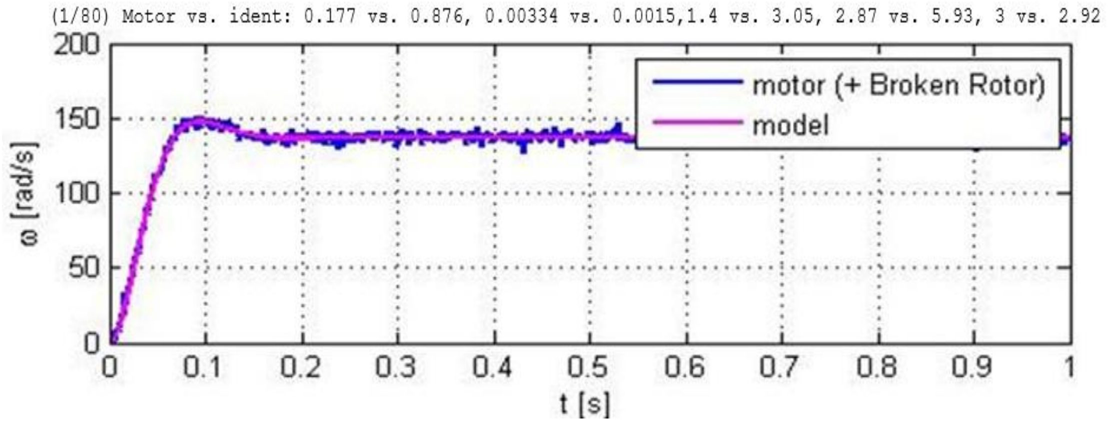

Figure 6.5 Modified Particle Swarm Optimization Technique for SEW EuroDrive Motor in BRB unhealthy condition

The below figures 6.6 and figure 6.7 shows the parameter convergence till 80 iterations using PSO and MPSO respectively:

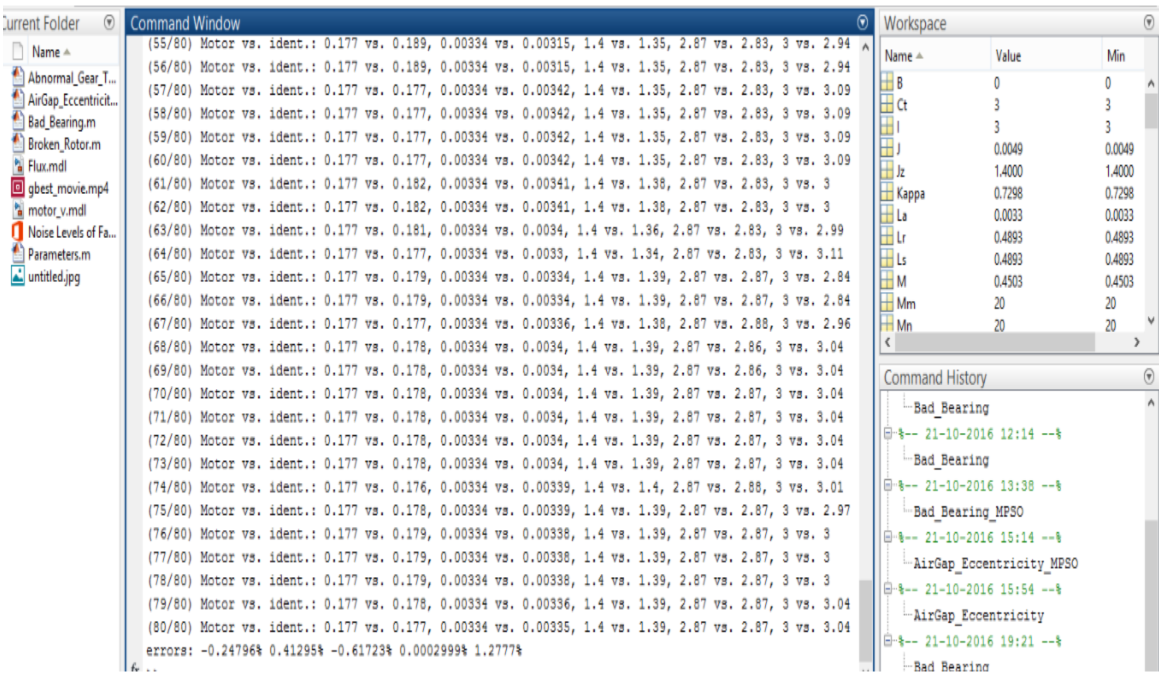

Figure 6.6 Error Convergence using Particle Swarm Optimization

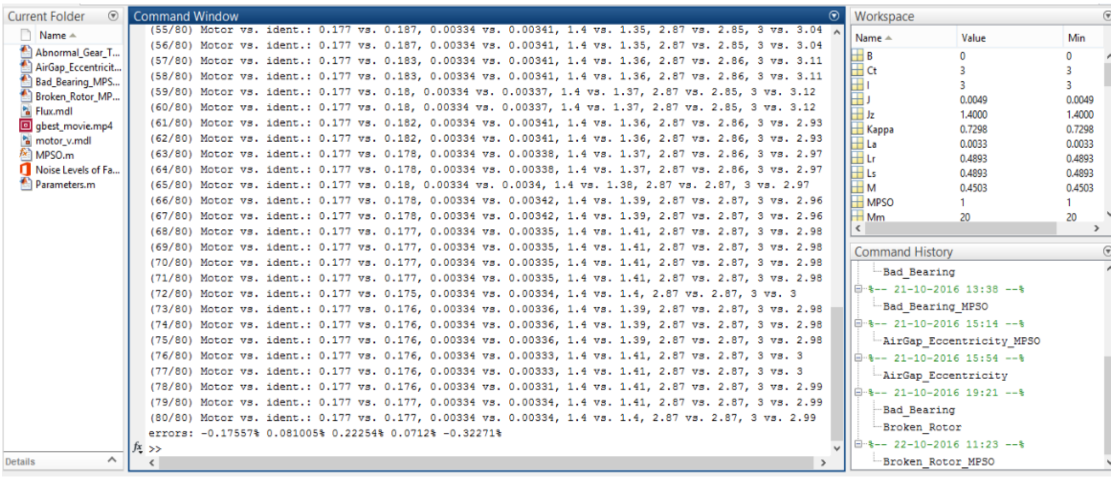

Figure 6.7 Error Convergence using Modified Particle Swarm Optimization

A comparative research between the results of Particle Swarm Optimization and Modified Particle Swarm Optimization is performed to verify the proposed method effectiveness. The below figures 6.8 shows the optimization results of magnetic flux using Particle Swarm Optimization and using Modified Particle Swarm Optimization given in figure 6.9 respectively.

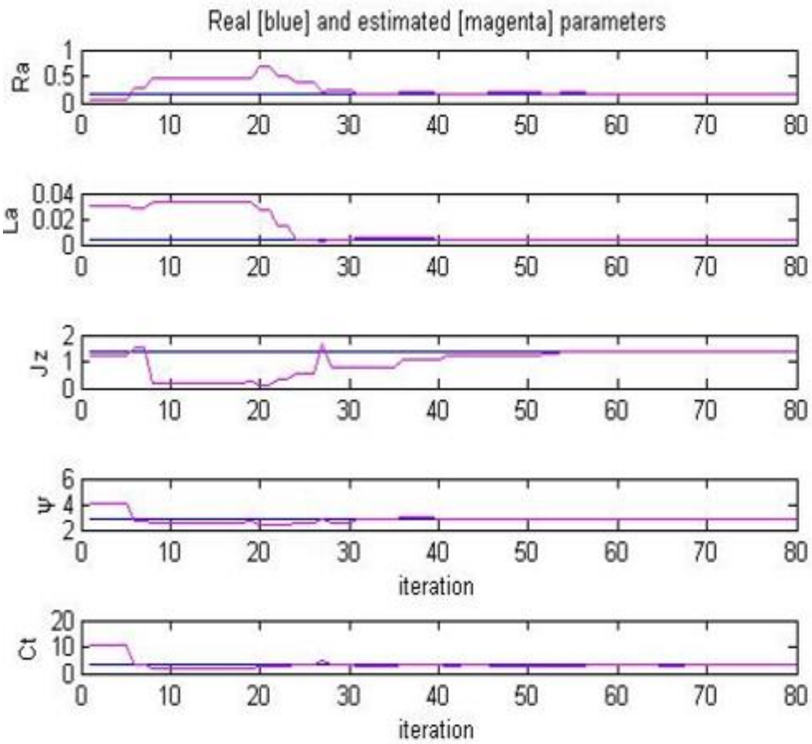

Figure 6.8 Results of Optimization for BRB fault using Particle Swarm Optimization Technique

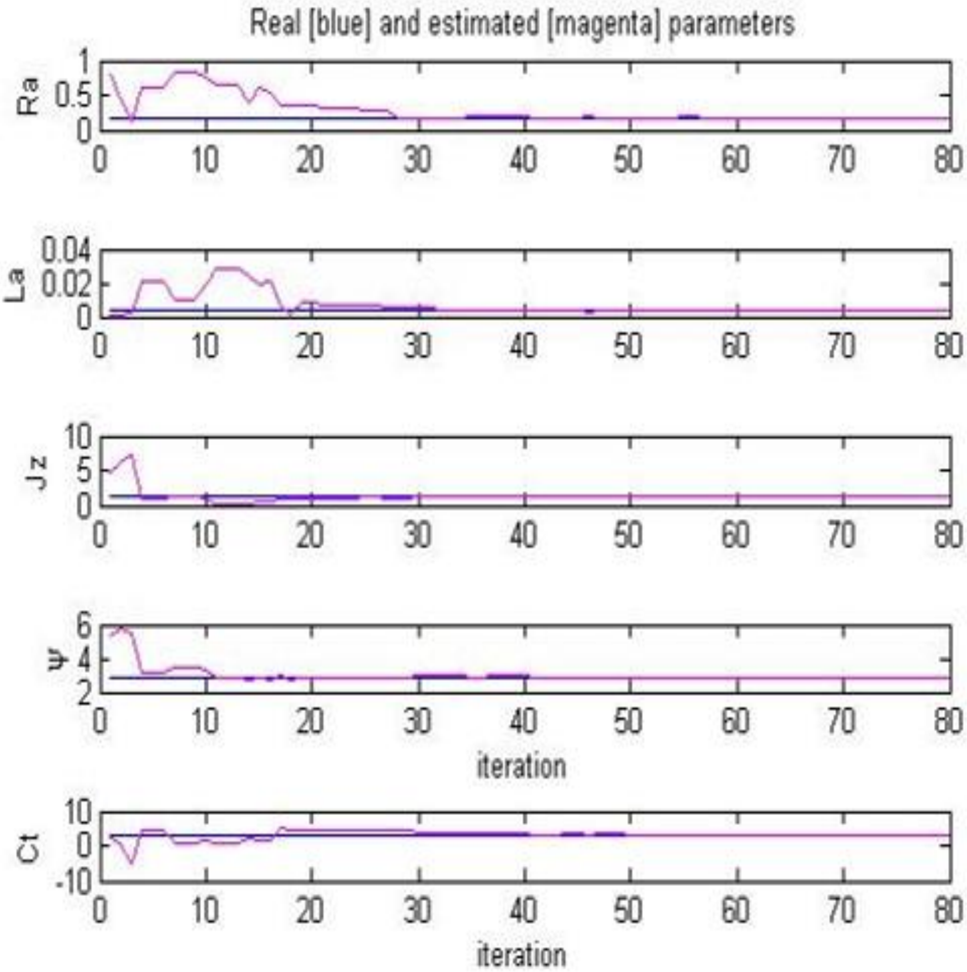

Figure 6.9 Results of Optimization for BRB fault using Modified Particle Swarm Optimization technique

Then the results are compared on the basis of error percentage to propose good techniques of optimization. The final comparison of results will be performed after acquiring the faults results. The results are compared in the below table 6.2 with graphical representation given in figure 6.10.

Table 6.2 Error Percentage using MPSO and PSO for BRB fault

Percentage of error					
Optimization	**Armature circuit resistance [Ohm]**	**Armature circuit inductance**	**Moment of inertia [kg*m^2]**	**Flux**	**Viscous damping coefficient [Nm/rad/sec]**
PSO	-0.24796%	0.41295%	-0.61723%	0.0002999%	1.2777%
MPSO	-0.17557%	0.81005%	0.22254%	0.0712%	-0.32271%

From the table it is evident that M-PSO optimizes armature circuit resistance, armature circuit inductance, moment of inertia and viscous damping coefficient with lesser percentage of error in case of broken rotor bar among all the parameter estimation. The two different optimization techniques are also graphically compared.

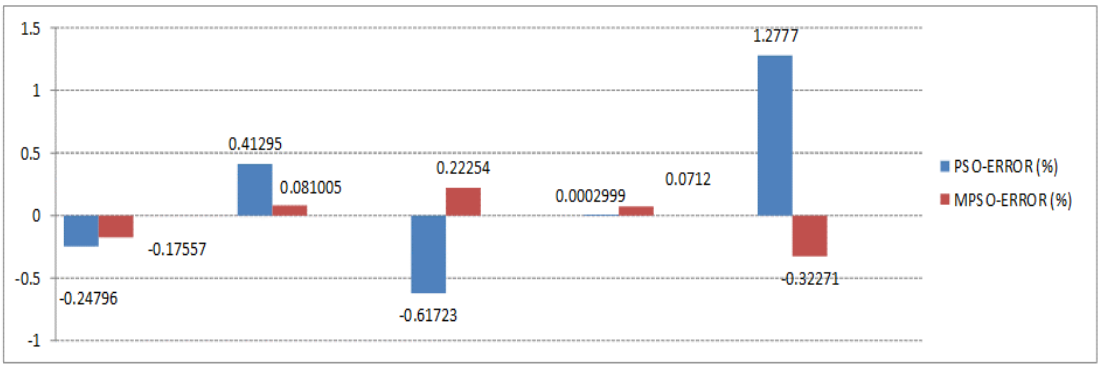

Figure 6.10 Graphical Error Percentage in MPSO and PSO

It can be inferred from the results that the Modified Particle Swarm Optimization technique optimizes the results rapidly with reduced error percentage in broken rotor bar case.

6.9 Summary

The broken rotor bar diagnosis in induction motor and the rotor fault effects on stator current spectrum of an induction motor has been examined through experimental results. The experiments are carried out using two techniques namely Modified Particle Swarm Optimization and Particle Swarm Optimization. The experiment reveals that the rotor fault influences two side bands mainly near the major stator current component. The analysis clearly reveals that the final approximation signal of faulty and healthy motors are different completely. The experiment is performed and the results show that Modified Particle Swarm Optimization technique optimizes the results rapidly with reduced error percentage in broken rotor case.

Chapter 7

Diagnosis and Performance of Abnormal gear teeth fault

7.1 Introduction

Gear is certainly considered as one of major equipment component in any industry. To certain extent, any fault in gears result in motor downtime, which eventually causes loss of production. Various techniques have been in practice in order to diagnose the defect in motor. Several methods have been performed to be capable of diagnosing the fault. The motor is joined with gear box. Above all, a gear defect for example a damaged tooth creates an aberration in the load torque observed by the motor.

7.2 Gear teeth fault and its effects

The induction motor, like any other electrical motors, is exposed to both electromagnetic and mechanical stresses. Gears are regarded as one of the primary components of electromechanical conduction in part of industrial applications. Any defect of a gearbox is likely to have a considerable effect on the machinery accessibility owing to the long-time required to eliminate the breakdown gearbox for restoration and replacement. In this perspective, there is a stable hunt for more advanced and effective gearbox diagnostic techniques [49]. Currently, vibration signal processing is considered as an effective and reliable technique for gear fault detection. Various techniques have been proposed in this field such as Cepstral analysis, and phase demodulation method and as well Cyclo stationarity analysis [209]. On the other hand, vibration measurement exhibited significant limitations for gear fault identification and also for diagnosis. According to [210] the most important drawback of this technique is the complicated placement and detachment in the arrangement of the vibration transducers that influences the sensitivity to the fitting position and the noise exist in background on account of exterior mechanical excitations.

Gears, in general, transfer the activity of rotor to the shaft of every load joined. Gears create a part of the mechanical load which is related with the motor. There are various types of faults that could happen in gear affects the operation of a system [211]. The most significant causes of gear fault are on account of irrelevant design of the gearbox, setting or configuration among the gears and application of inadequate heat treatments.In recent times, the spectral content of the current space vector has been employed for the analysis of gear tooth localized fault (for example pinion fault) [212] [213]. added that it has been exhibited by analytical calculation that the current space vector signature analysis includes fault signature information akin to the mechanical torque tested by the driven electrical machine.

The variation of torsional vibrations between strong and defective conditions of a gear results in differences in the rotating speed and motorized torque of the gearbox. Also, these differences will consequently instigate changes in air-gap torque, consequently producing sidebands across the fundamental of stator currents of a generator in which the gearbox is attached. The causes of motor defects are categorized to rotor, gear, and windings of motor and various ecological causes. In general, diagnostic techniques are to assess the noise and vibration [214]. Besides, the motor could be diagnosed even on working condition. Causes of defect of a gear are generally from the machining precision, damaged gear teeth and other gear components, mixing with debris, and so on. [215]. with a gear failure and explored fault diagnosis by current and some vibration techniques.

Gear faults will result in defect of transmission or even breakdown of the entire machines. Consequently, to develop the monitoring techniques and diagnosis tools for identifying the gear ratios and faults, shaft asymmetrical in the gearbox and the current traversing through the motor running, there has been a stable development progressing in these monitoring techniques. Techniques for example wear and debris analysis and acoustic emissions demand ease of access to the gearbox either to accumulate samples or to organize the electrical device or near the gearbox. However grimy atmosphere, background noise and structural vibration might hinder the quality and effectiveness of these methods. Consequently, there is a demand to examine the gearbox ahead of its actual location that could be accomplished through MCSA which has already been effectively employed for health monitoring of induction motor. Any fault in gears result in machine downtime giving rise to a loss of production. Various techniques have been largely employed so as to diagnose defects in gears. FFT is a versatile method employing which the frequency content of a signal could be identified. [176] have quoted the effectiveness of MCSA in identifying the small sidebands of the tooth mesh frequency. [216] examined the application of wavelet functions for automatic gear fault diagnosis and intended to establish MCSA as the basis of health monitoring of a multi-stage gearbox. The condition monitoring integrates two most important sources of vibration, which include load fluctuation and faults in gears. FFT analysis relates the elements of steady vibration analysis and current signatures. The disadvantage of this technique is based on the point that good time resolution will lead to poor frequency resolution and conversely, in accordance with the uncertainty principle.

In both gear and bearing defect diagnosis, study has emphasized that acoustic emission sensors are more responsive to early defects than vibration analysis. Compared with vibration analysis, acoustic emission signals have the prospective to identify small abnormal resistance, early cracking, etc. There are some prospective justifications for this. The first one is that acoustic emission discharged by very small faults takes place in frequency ranges which are greater than the operational extents of vibration sensors and consequently might not be captured by vibration sensors. The second justification is that once there is only a small fissure or surface wear in the machine, it is not critical enough to transform the structural vibration. [217] emphasized that high contact ratio of gears is considered as a significant element for gearbox noise reduction.

7.3 Condition monitoring of gear faults

Fault diagnosis of Induction motor-gearboxes is of critical significance and has been investigated for several years. A different feature of gearbox faults in induction motor is that they frequently create vibration signals. In the frequency domain, this is replicated by the intensification of the sideband constituents in the interrelated meshing frequencies and their harmonics. Generally, a localized defect for example tooth crack stimulates transients into the background vibration that leads to a sequence of side band frequencies in the spectrum. Spectral analysis is generally efficient in identification of such faults. [218] specified that in the initial development period of the localized defects, the side band components are difficult to identify from the spectrum since they are disseminated in broad frequency bands and might intersect with some background elements. According to [219] comparatively a technique that takes minimal time to adjust to new samples is better performing than the slow paced frontward and backward pass technique in neural networks.

Health monitoring of electric motors is a method of increasing significance, as defect tolerant techniques are becoming essential in various applications. Early diagnosis of motor defects is a fundamental pillar so as to accomplish complete tolerance by the maintenance of defective parts in motors. As far as electric drives are taken into account, the ratio of mechanical faults (such as, gears) is extremely high. The mechanical fault identification is generally on the basis of vibration signals, a strong and efficient technique, which is moderately invasive and with increased latency. Signal processing techniques are largely employed for health monitoring to deal with common issues [220]. In fact, health monitoring of electrical faults on the basis of space–vector (SV) of electrical signals is well–recognized approach. Mechanical defects specifically gear faults and mechanical differences are largely monitored by vibration signals. Vibration monitoring is extensive and depends on common standards and is acquired by sensor positioned on the exterior part of motor and they are quite consistent and established. Vibration spectra could be examined and some "signature" could be isolated which are associated with particular mechanical issues including imbalances, misalignment, slackness, curved shaft and bearing issues, the gear faults being the most risky and likely. The application of current signals for health monitoring of mechanical defects is extended to the analysis of gear defects with different various approaches [221]. In this framework, a one-stage gearbox is generally considered, for which particular signatures could be recovered in the stator current spectrum all around the supply frequency and this technique can be effectively extended to health monitoring of tooth breakage defect in multistage gearboxes. In this state, certain signatures emerge in the stator current spectrum and are associated with the gear mechanical frequency elements. In recent times, health monitoring of gear tooth damage (generally denoted as gear tooth fault) on the basis of space vector instantaneous frequency has been developed by [222].

Tracking of the revolving speed of gearbox is not simply efficient in monitoring the gearbox. As stated by [223] the reason behind is that the gearbox covering vibration is imparted to the gearbox by means of adaptable rolling element bearing, and extremely large stimulation of the gearbox occurs on account of various time-varying factors such as tooth mesh hardness, frictional forces and bearing forces; thus, resulting in a large speed variability.

The main sources of vibration within an induction motor-gearbox are the rotating components that are the gears and bearings. In a gear transmission system, the primary source of vibrations is generally the meshing action of the gears. In terms of a fault tooth, the gear diagnostic algorithm should identify the occurrence of a tooth crack soon after its inception and later executes diagnosis to define its location (pinion, number of defective teeth) and dimension. [224] proposed Hilbert transform to carry out both identification and diagnosis. Tooth crack is made happen by the descending action between the teeth that exist at each side of the pitch circle, however not within pitch circle. Consequently, crack will not be consistent all the time. Crack which is non-consistent for all teeth will result in a misrepresentation of the tooth-meshing frequency that will create vibration at the tooth-meshing rate and its harmonics. These might not be noticeable up till they become greater than the consequences on account of tooth fissure. [224] employed Hilbert transform for identification of induction motor-gearbox faults and proposed method is proven to be efficient for identification of early gear faults in induction motor. Detection at its very initial stages and diagnosis of gear. faults are considered critical to stop the system from breakdowns which might cause damage or whole system halt. Until now, fault diagnosis of gearboxes has gained detailed study for several years, and vibration analysis of these motors could find some kinds of faults. Determination of all kinds of these faults comprises in itself an effective monitoring technique. A few monitoring techniques employed for gears are considered uncomplicated to apply like the scalar descriptors [226] and spectral analysis (FFT and cepstrale analysis) [227]. The diagnosis accordingly demands more advanced signal processing techniques. It is also significant to define the dynamic loads on every part of their constituents (, teeth, bearings), the level and difference of local pressures in these elements or find transient phenomena.

7.4 Various techniques for abnormal gear fault

Recent researches are considering more challenging defects for example bearing defects or even gear faults in the gearbox. This experiment is of great concern in applications wherein the mechanical system is not simply accessible for conventional vibration measurements. Motors are often connected with mechanical loads and gears. A number of faults are as well could take place in mechanical arrangement. Examples of those defects are connecting misalignments and defective gear systems that connect a load to the motor. The reasons of the gear failure are generally from the broken tooth, gear materials, lubricating systems, etc. When taking the meshing of gears into account, the tooth mesh hardness is differing since the amount of meshing tooth is intermittently varying. In addition, when a defective tooth is coming into system the hardness is likely to drop abruptly, therefore tempting a rapid reduction of the load torque and accordingly of the current space-vector amplitude. Also, in actual fact the current spectral signature might get polluted by increased frequency components that intensify a problem in the diagnosis.

7.5 Optimization

A gear includes a pinion and a driven wheel. A gear fault for example damaged tooth creates a fault in the load torque of the motor and therefore whenever the abnormal tooth meet driven wheel, motor is likely to face a failure giving rise to uneven torques and variation in air-gap eccentricity. In consequence the fault is likely to transmit from the load to the motor current. Based on the abnormality unique frequency equation (12) is represented in the spectrum.

$$f_e = f_s \pm kf_r \tag{12}$$

Where f_e = Current components due to air gap eccentricity

$k = 1,2,3\ldots..$

f_s= Supply frequency

f_r = Rotational speed frequency of rotor

And f_r can be calculated as equation

$$f_r = \frac{f_s}{n\,(\frac{p}{2})} \quad (13)$$

Here n = gear ratio,

p = Number of pole pairs

For the abnormal gear teeth optimization, reference has been taken for Fault frequencies, which are later put into the MATLAB/SIMULINK model. Rest of the parameters are kept same as of the real SEW Euro Drive Motor.

Here [LSB = 500Hz and USB = 550Hz] are taken as reference range [227] to optimize the faulty gear box behavior of the induction motor.

Applying the PSO and MPSO on the following initialized motor parameters, and later the results are compiled through MATLAB/SIMULINK.

Test motor parameters

Ua	=	Rated Armature Voltage [V], 420V
Mm	=	Rated torque [Nm], 20Nm
I	=	Rated Current [A], 3A
Ra	=	Armature Circuit Resistance [Ohm], 0.177ohm
La	=	Armature Circuit Inductance [H], 0.00334H
N	=	Rated speed [RPM], 1395
W	=	N*pi/30; Rated speed [rad/sec]
Jz	=	1.4; Moment of inertia [kg*m^2]
psi	=	(Ua-Ra*I)/W; Flux
Ct	=	3; Viscous Damping Coefficient [Nm/rad/sec]
LSB	=	500Hz
USB	=	550Hz

The optimization has been done with the PSO and MPSO and abnormal gear teeth fault. Figure 7.1 represents the behavior in defective condition in PSO and Figure 7.2 depicts the defective condition in MPSO.

```
(1/80) Motor vs. ident: 0.177 vs. 0.587, 0.00334 vs. 0.011, 1.4 vs. 1.31,2.43 vs. 3.97, 3 vs. 4.94
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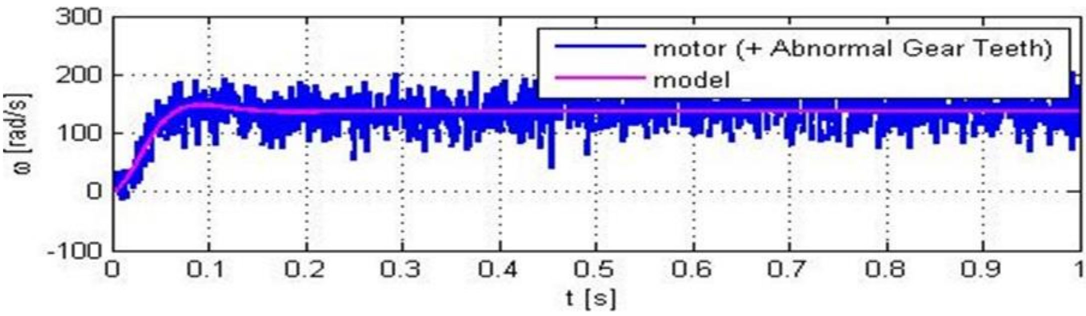

Figure 7.1 PSO Technique for a SEW-Euro Drive Motor in Unhealthy condition of gear teeth fault

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(1/80) Motor vs. ident: 0.177 vs. 0.5, 0.00334 vs. 0.011, 1.4 vs. 9.35, 2.87 vs. 3.84, 3 vs. 12.85
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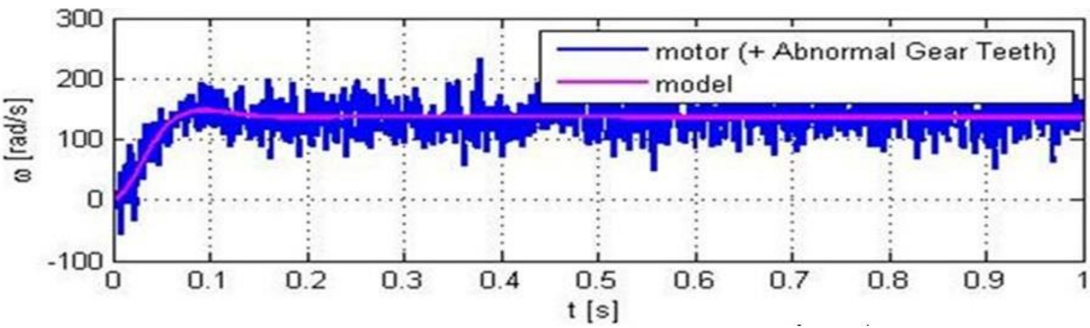

Figure 7.2 M-PSO Technique for a SEW-EuroDrive Motor in Unhealthy condition of gear teeth fault

Parameter convergence through PSO and M-PSO techniques are shown below till 80 iterations in figure no. 7.3 and figure 7.4 respectively. In the end of the 80 iteration cycles the corresponding percentage error are also captured and further analysed for the comparison purpose.

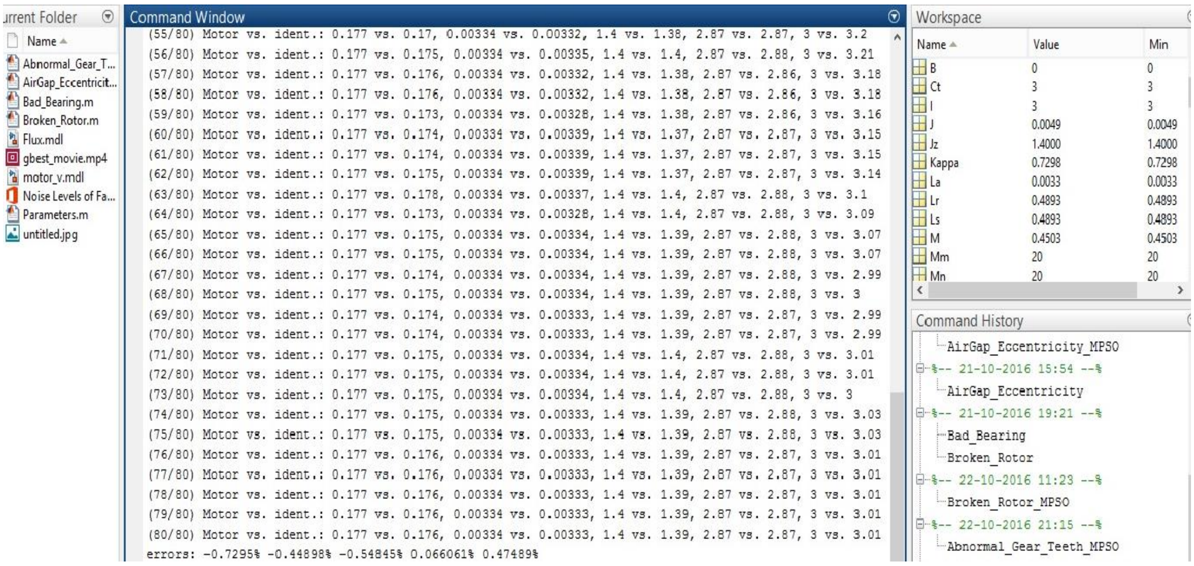

Figure 7.3 Error Convergence using Particle Swarm Optimization

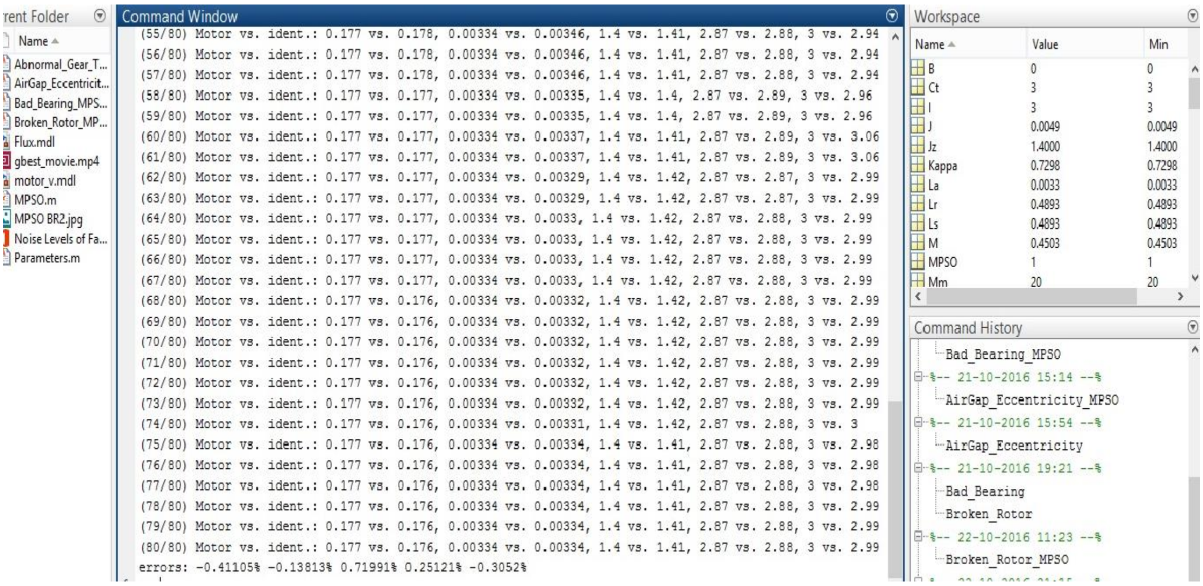

Figure 7.4 Error Convergence using Modified Particle Swarm Optimization

In addition, a comparative analysis has been done based on the results of the MPSO and PSO in order to verify the efficiency of the proposed technique. Figure 7.5 and 7.6 represent the parameters optimization results with PSO and MPSO correspondingly.

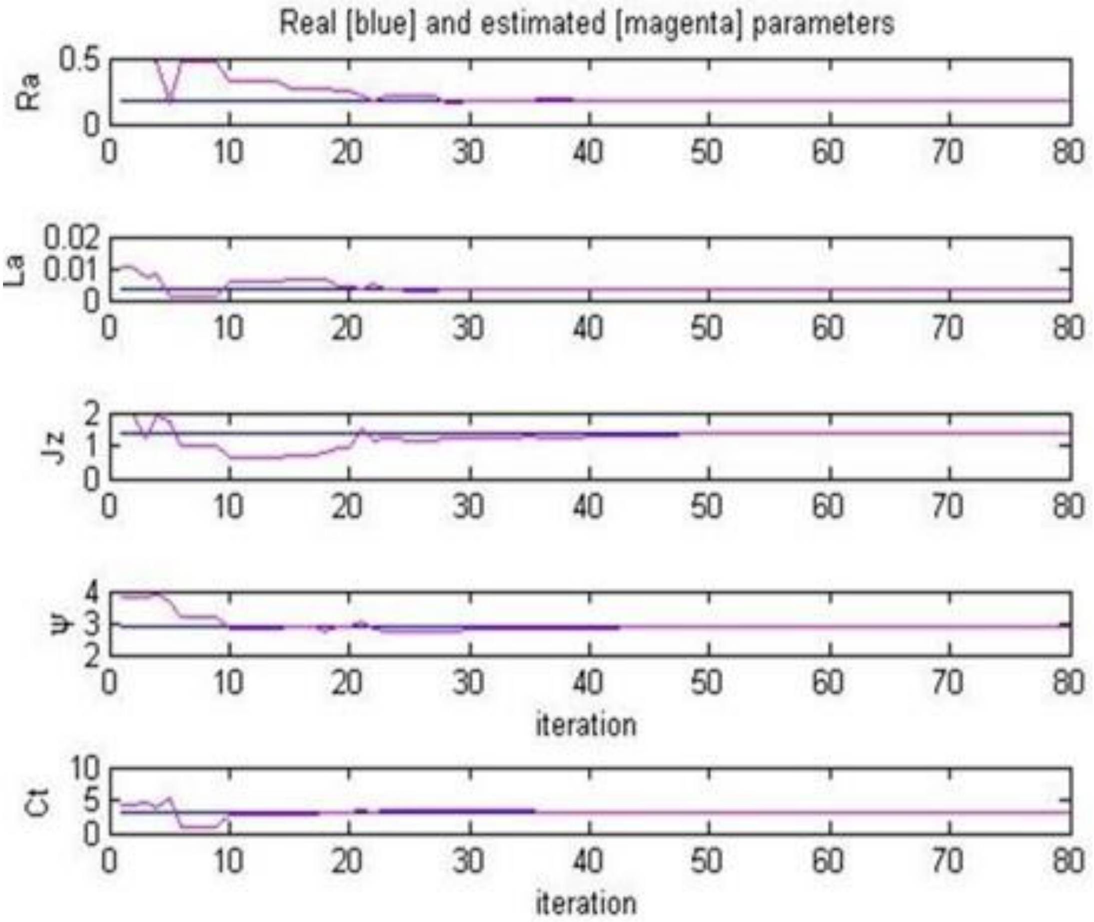

Figure 7.5 Optimization results for the abnormal gear teeth fault using PSO

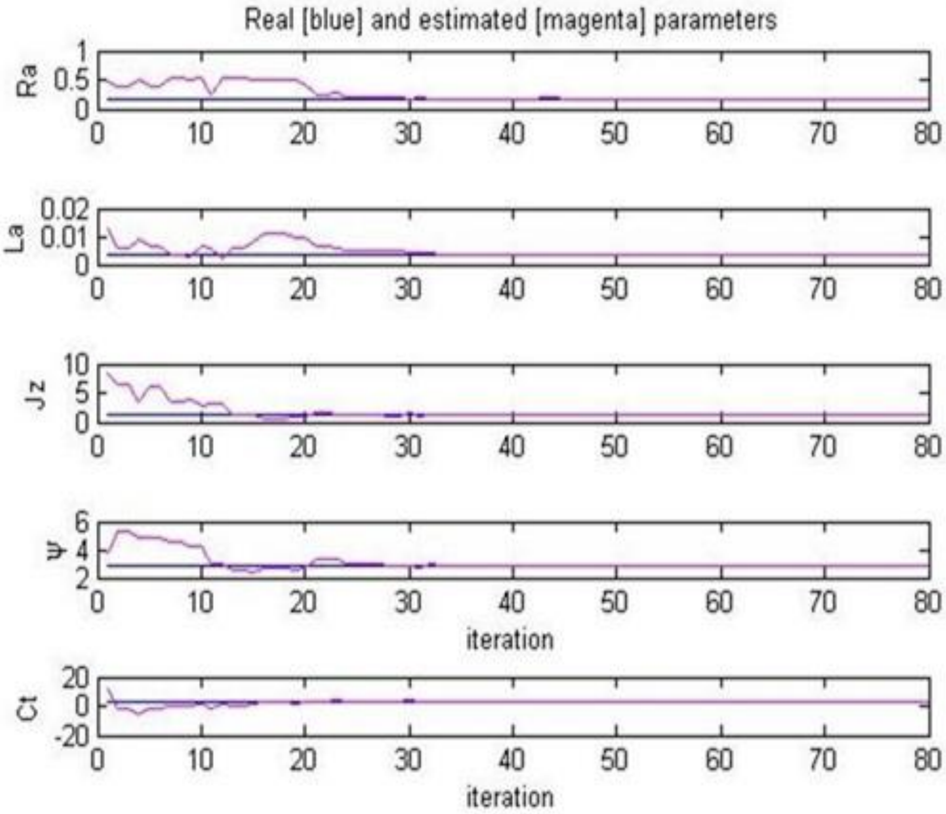

Figure 7.6 Optimization results for the abnormal gear teeth fault using MPSO

Comparison has been done for the outcomes based on percentage of error in order to propose the better optimization techniques. The comparison results are given in the below table 7.1 with the graphical representation in Figure 7.5 respectively.

Table 7.1 Percentage error using PSO and MPSO for abnormal gear teeth fault

Percentage of error					
Optimization	**Armature circuit resistance [Ohm]**	**Armature circuit inductance**	**Moment of inertia [kg*m^2]**	**Flux**	**Viscous damping coefficient [Nm/rad/sec]**
PSO	-0.72950%	-0.44898%	-0.54845%	0.066061%	0.47489%
MPSO	-0.41105%	-0.13813%	0.71991%	0.25121%	-0.30520%

It is evident from the table that armature circuit resistance, armature circuit inductance and viscous damping coefficient are optimized with less percentage of error by M-PSO and other two by PSO respectively.

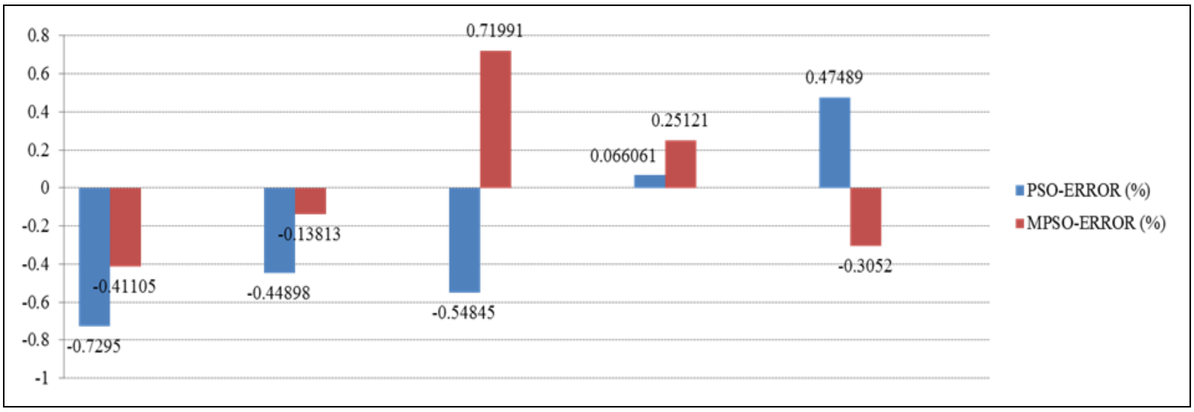

Figure 7.7 Graphical percentage error in PSO and MPSO

It is clear from the obtained optimization results that the MPSO technique optimizes three parameter results faster with less percentage of error in case of abnormal teeth.

7.6 Summary

In this chapter, a technique of gear fault identification using various properties of electrical currents in induction motor-based systems is developed. A technique such as MCSA, neural network and FFT are combined for gear fault identification in electromechanical systems. This technique is receptive to enhancement, particularly in terms of its categorization potential to facilitate difference between defect types. Analyzed findings exhibit that the proposed technique is considered efficient for identification of induction motor-gear faults at its incipient stage. Also the proposed technique is assumed to have the benefits of accurateness, effectiveness, and ease of locating defects by visual inspection. The technique proposed in the study has been broadly employed in various applications and has exhibited effective results in the incipient identification of mechanical defects. In addition to early detection, this process could help differentiate the real cause of failure by examining the actual system fault frequencies.

Chapter 8

Conclusion, Validation and Future Scope

8.1 Introduction

The underlying principle of this research work is to analyze the potential of flux monitoring technique to in identifying various faults in an induction motor. The efficacy of this monitoring technique has been assessed with regard to some other parameters employed for fault identification, such as MCSA, signal processing, neural network, wavelet transform, fuzzy algorithm, etc. Also, the current chapter is derived from based on the findings and also dealt with various diagnostic techniques related to induction motor. The area of interest for this research work is limited to induction motors alone.

8.2 Summary and Conclusions

In this research work, the numerous common type of abnormalities are validated through experimental setup. As previously explained, electrical motors are subjected to an extensive range of mechanical issues regular to most machines, for example unbalance, misalignment, bearing and gear faults, and quality, but electrical motors as well face their own particular set of troubles that are actually a consequence of electro-magnetic generated fields in the stator and rotor. This has explained in the previous sections of this research work, there is a critical demand to search for a fault indicator which is capable of pointing out broken rotor faults, air gap eccentricity-related abnormalities and bad bearing and gear faults. In this aspect, the flux monitoring technique that interrelate with the fundamental harmonic of the motor and generate the forces has been investigated to identify their capability to detect motor abnormalities, various kinds of eccentricity faults. This flux monitoring approach is considered as an innovation in the area of fault diagnosis in induction motors. At the primary stage of research work, an experimental setup is established in order to get a healthy spectrum of Induction motor at no load through FFT technique. Further the bad bearing abnormality is introduced by damaging the inner race of the bearing and thereby using the FFT algorithm which monitors the faulty frequencies amplitude and follows the change in their amplitude with time. A prominent variation in amplitude signifies an emerging fault. The benefit of employing a detection technique based on flux monitoring has been suggested by the research work and this detection technique is considered more unfailing than the MCSA that delivered no useful information regarding the defect being studied. Bearing faults could be obtained effortlessly in frequencies which are adapted with the essential frequency of the supply. Further, the experimental outcomes of fault frequencies are taken as references for optimization techniques for PSO and MPSO. Induction motor models are structured on the basis of appropriate mathematical descriptions that have significant dynamic categorization of the processes related with induction motor function in both healthy and defective conditions. The PSO and MPSO technique is asserted to be regardless of the load level, velocity, and control loop bandwidth of the motor systems. Though, it necessitates a precise mathematical model of the whole driving structure, such as the control loop parameters that might not be accessible or of which the parameters are time changeable on account of aging or change of functioning conditions. Model based techniques have been broadly executed for five different parameters of induction motor and comparative study has been done for the outcomes on the basis of percentage of error in order to suggest the better optimization techniques. The benefits of model based techniques are: they are considered no-invasive and application costs are likely to be low. The study employs the mathematical model in SIMULINK/MATLAB setting; MATLAB / SIMULINK model has been selected for the execution of the healthy induction motor model.

Experimental setup and optimization implemented for four different faults (Bad bearing fault, Air gap eccentricity, Broken rotor bars and abnormal gear teeth) and the effect on the magnetic flux is exhibited with the help of FFT technique. Further progressed to examine the capability of the electromagnetic flux obtained in induction motor for the above four abnormalities. From the findings, it has been identified that the signs imparted by the search coil likely to observe the electromagnetic flux all-around a stator. This is for the reason that the results of system depends upon coil position and also flux magnitude dependant. It is an essential suggestion of this research work that blending the concomitantly observed information from excess of one coil will give an additional position dependant information resource that is not considered when using usual MCSA techniques. It is also determined to use search coils to monitor induction motor devices as they are considered well-suited to the research of the rapid fluctuations which would take place in the stator flux as a result of modulation arising from energy fluctuations on account of defect conditions and disruptions within the field as a result of rotor radial and axial arrangements stemming from defects on the system. It is predicted that the flux monitoring technique, specifically when coupled with other techniques for example MCSA, signal processing, neural network, vibration monitoring, etc, could be employed to enhance the consistency of extant systems.

The research work concluded that a future prospect of condition monitoring of induction motors by signal processing and various optimization techniques in the manufacturing and engineering field. The greater part of research work has employed a single sensor type associated with a specific signal processing technique in order to find a given fault. This work has presented a research in health monitoring and has found out key areas for future studies.

The hybrid approach to monitor the health with single sensors clearly illustrates the lost cost health monitoring techniques of the Induction motors which will enhance the durability of the motors in near future. The fast growing computational supremacy of personal computers can allow researchers to implement these low cost but efficient optimization algorithms to verify the optimum parameters of induction motors and monitor the health of Induction motors.

8.3 Contributions

The prime goal of the research work is to analyze the common mechanical and electrical faults practically with the support of FFT signal processing technique. An experimental setup is designed for a steady and precise analysis of Induction motor that can introduce a specific fault in separation to other faults in the motor. A search coil is used to monitor the magnetic flux variation through FFT technique. In the research work, along with the experimental setup, MATLAB/SIMULINK environment is used in order to perform the PSO and MPSO techniques. The contribution is summarized below for the research below:

1. Survey in below areas are completed

    - Numerous health and condition monitoring techniques and fault diagnosis approaches in view of practical test benches requirement.
    - Magnetic flux monitoring techniques.
    - Various Optimization methods.

2. Detailed study of electrical and mechanical faults in Induction motor.

3. FFT analysis and Optimization for the bad bearing fault in Induction motor.

    - A comprehensive analysis for bad bearing fault (Inner race) has been established.
    - An experimental study for bad bearing fault with help of Fast Fourier Transform. (FFT) under no load condition has been depicted in the research.
    - The effect of abnormal magnetic flux has been studied
    - The experimental setup is also implemented through MATLAB/SIMULINK with Fault Frequencies introduced and further optimized by PSO and MPSO both.
    - Comparative study was also conducted for the outcomes on the basis of percentage of error.

4. FFT analysis and Optimization for the air gap eccentricity fault in Induction motor.

    - Static air gap eccentricity studied and performed on the test bench and further diagnosed with the FFT in the research work.
    - MATLAB/SIMULINK model for induction motor is executed with Faulty frequencies taken from experimental results and then optimized through PSO and MPSO.
    - Percentage of error calculated for the PSO and MPSO outcomes and comparative study is finished.

5. FFT analysis and Optimization for the broken rotor bar fault in Induction motor.

    - Practical implementation of Broken rotor bar fault on the test bench.
    - FFT technique is successfully implemented for broken rotor bar and faulty frequencies introduced in MATLAB/SIMULINK model in order to execute the optimization techniques.

- Outcomes of PSO and MPSO are compared.

6. MATLAB/SIMULINK model for induction motor is executed and the faulty frequency referring to the abnormal gear teeth is implemented in the model. And then percentage of error in both of the PSO and MPSO optimization techniques is evaluated.

The signal processing techniques, FFT and Optimization techniques are used for the different kinds of faults of Induction Motor e.g. bearing failure , air gap eccentricity , broken rotor bar fault, abnormal gear teeth fault and has been examined in this research work. The present work is published in journals and conference.

8.4 Validation of the work

These days, no one could refuse the significant role of the induction motor in industry applications. It is recognized fact that a disruption of a manufacturing process as a result of a mechanical or electrical problem produces a major financial loss for the sector. In general, fault could be categorized as stator or rotor defect based on the location of the defect [153]. Damages could be caused by rotor faults, stator faults, rotor-stator eccentricity and bearing faults. To inhibit such problems, it is important to identify these defects to prevent a major failure from taking place. Broken rotor bars hardly ever cause immediate defects, particularly in large multi-pole motor. Though, if there are enough BRBs, the motor might not start off as it might not be capable of developing adequate accelerating torque and different methodologies have been suggested to detect BRBs in induction motors [37]. The current study also dealt with gear tooth faults. The subject of motor health monitoring identifies those issues, and increasingly more relative studies are being dedicated to it by industry and academic world. With health monitoring, an incipient defect has the ability to detect at a very initial stage [40,8,9] investigated induction motor fault analysis with the application of FFT and similarly current study has also used FFT analysis. A FFT based analysis and health appraisal system has been suggested and executed and this application facilitates fast failure condition analysis. A potential project is diagnostic method on electrical machines with support of MCSA and FFT so as to recognize small size, rapid response and portability of the complete diagnostic analysis in the future [225]. The techniques discussed can be used in laboratory as well as in industries to diagnose the common faults of induction motor. The results obtained from these techniques reveals that these techniques may be helpful, as presented in this thesis, to reduce the downtime of Induction Motors and to improve the overall efficiency of production system.

8.5 Scope for future work

This study investigated about the health monitoring and fault diagnosis of induction motors. The study presented a broad view of the fault indicators generally employed for finding the defects in motors, with a special interest on electromagnetic flux monitoring, as the current paper depends only on the indications given by these parameters. This study analyzed about potential of flux monitoring technique to in identifying various faults in an induction motor. This research has analyzed only four faults such as bad bearing fault, air gap eccentricity, broken rotor bar, and abnormal gear tooth fault. In future, this study can be extended by identifying other faults in an induction motor. The scope for the future can be summarized in below listed points:

i. Numerous problems encountered in real life cannot be actually formulated as a single objective problem; hence the requirement of Multi-Objective Optimization (MOO) has arisen to optimize the faulty condition.

ii. It is marked from the work performed so far that there is always a future scope of health monitoring of not only induction motors by signal processing and optimization techniques across the industries but can be extended for DC motors also.

iii. A hybrid technique can be introduced which consists of hardware setup and computational Optimization algorithm to monitor the healthy magnetic flux of induction motor by making it as a primary fitness function and thus helps to lessen the maintenance cost, to forecast the machine failure, to standardize the motor performance, to enhance machine reliability, and also to enhance the accurateness in failure prediction.

References

[1] Siddiqui, K. M., Sahay, K., & Giri, V. K. (2014). Health monitoring and fault diagnosis in induction motor-a review. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, *3*(1), pp 6549-6565

[2] Bendiabdellah A., Benouzza N., Toumi D., (2006). Cage rotor Faults detection by speed estimation and spectral current analysis. The 3rd IET International Conference on Power electronics, Machines and Drives (PEMD 2006), April 4-6, 2006, Dublin Ireland.

[3] Boudinar, A.H., Bendiabdellah, A, Benouzza, N, Boughanmi, N. (2007). Three Phase Induction Motor Incipient Rotor's Faults Detection Based on Improved Root-Music Approach. International Review of Electrical Engineering, 2(3), pp. 1-9

[4] Kumar, D.D. (2010). An investigation into fault diagnosis of induction motor by artificial intelligent technique. Retrieved on 26th August 2019 from http://hdl.handle.net/10603/174822

[5] Ghate, V, Dudul, S. (2010). Optimal MLP neural network classifier for fault detection of three phase induction motor. Expert Systems with Applications, 37(4), pp. 3468-3481.

[6] Merizalde, Y, Hernández-Callejo, L, Duque-Perez, O. (2017) State of the Art and Trends in the Monitoring, Detection and Diagnosis of Failures in Electric Induction Motors. Energies, 10(1056), pp. 1-32.

[7] Aroui, T, Koubaa, Y, Toumi, A. (2007). Application of feedforward neural network for induction machine rotor faults diagnostics using stator current. J. Electr. Syst, volume 3, pp. 213–226.

[8] Narwade, S, Kulkarni, P, Patil, C.Y. (2013). Fault Detection of Induction Motor Using Current and Vibration Monitoring. International Journal of Advanced Computer Research, 3(4-13), pp. 272-279.

[9] Narwade, S, Kulkarni, P, Patil, C.Y. (2013). Types of Fault. As Cited in Narwade, S, Kulkarni, P, Patil, C.Y. (2013). Fault Detection of Induction Motor Using Current and Vibration Monitoring. International Journal of Advanced Computer Research, 3(4-13), pp. 272-279.

[10] Subhasis, N. (2006). "Detection of stator faults in induction machines using residual saturation harmonics", IEEE Transactions on Industry Applications, 42(5).

[11] Mirafzal, B, & Demeradash, N.A.O. (2006). "On innovative methods of induction motor interturn and broken bar fault diagnostics", IEEE Transactions on Industry Applications, 42(2).

[12] Biju, K, Jagadanand, G. (2010). Fault Detection of Induction Motor using Energy and Wavelets. Proc. of Int. Conf. on Control, Communication and Power Engineering, pp. 210-214.

[13] Douglas, H., Pillay, P., Ziarani, A., 2005, "Broken Rotor Bar Detection in Induction Machines with Transient Operating Speeds", IEEE Transactions on Energy Conversion, Vol. 20, No.1, March, pp. 135-141.

[14] Boga lecka, P.K., & Bieta, E. (2009). Broken rotor bar impact on sensorless control of induction machine. The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, 28(3), pp.540-555.

[15] Faiz, J., Ebrahimi, B., Asaie, B., Rajabioun, R., & Toliyat, H. (2007). A criterion function for broken bar fault diagnosis in induction motor under load variation using wavelet transform. International Conference on Electrical Machines and Systems, ICEMS, pp. 1249 –1254

[16] Yang, C., Cui, G., Wei, Y., & Wang, Y. (2007). Fault Diagnosis for Induction Motors Using the Wavelet Ridge. Second International Conference on Bio-Inspired Computing: Theories and Applications, BIC-TA, pp. 231 – 235.

[17] Pineda-Sanchez, M., Riera-Guasp, M., Antonino-Daviu, J. A., Roger-Folch, J., Perez-Cruz, J., & Puche-Panadero, R. (2010). Diagnosis of Induction Motor Faults in the Fractional Fourier Domain. IEEE Transactions on Instrumentation and Measurement, 59(8), pp.2065 - 2075.

[18] Cabal-Yepez, E., Osornio-Rios, R., Romero-Troncoso, R., Razo-Hernandez, J., & LopezGarcia, R. (2009). FPGA-Based Online Induction Motor Multiple-Fault Detection with Fused FFT andWavelet Analysis. International Conference on Reconfigurable Computing and FPGAs, pp. 101 –106.

[19] Gaeid, K.S., Ping, H.W. (2011). Wavelet Fault Diagnosis of Induction Motor. MATLAB for Engineers - Applications in Control, Electrical Engineering, IT and Robotics, pp. 341-364.

[20] Wesley G. Zanardelli, E. G. (2005). Wavelet-based methods for the prognosis of mechanical andelectrical failures in electric motors. Mechanical Systems and Signal Processing , 19 (2), 411–426.

[21] Schmitt, E, Idowu, P, Morales, A. (2008). Applications of Wavelets in Induction Machine Fault Detection. American Society for Engineering Education, pp. 1-10.

[22] Jimenez, G.A., Munoz, A.O., Duarte-Mermoud, M.A. (2007). Fault detection in induction motors using Hilbert and Wavelet transforms. Electrical Engineering, volume 89, pp. 205–220.

[23] Pires, V.F., Kadivonga, M, Martins, J, Pires, A. (2013) Motor square current signature analysis for induction motor rotor diagnosis. Measurement, volume 46, pp. 942- 948.

[24] Kim, Y.H., Youn, Y.W., Hwang, D.H., Sun, J.H., Kang, D.S. (2013) High-resolution parameter estimation method to identify broken rotor bar faults in induction motors. IEEE Transactions on Industrial Electronics, volume 60, pp. 4103-4117.

[25] Antonino-Daviu, J, Gyftakis, K, Cardoso, A.M. (2016) A reliable indicator to detect non-adjacent broken rotor bars severity in induction motors. International Conference on Electrical Machines (ICEM).

[26] Siddiqui, K.M., Sahay, K. (2016) Early, Diagnosis of Airgap Eccentricity Fault In The Inverter Driven Induction Motor Drives By Wavelet Transform. Journal of Electrical Engineering,

[27] Gama, R.S.D., Silva, C.C.J., Nascimento, C.E.F., Silva, A.M.D., Costa, C.D. (2017). Analysis of Combined Motor Current Signature and Vibration-Monitoring Techniques in the Study of Broken Bars in Three-Phase High-Performance Induction Motors. Journal of Electrical & Electronic Systems, 6(3), pp. 1-7.

[28] Koca, Y.B., & Unsal, A. (2017). A Review on Detection and Monitoring of Stator Faults of Induction Motors. International Journal of Innovative Research in Science, Engineering and Technology, 6(10), pp. 70-74.

[29] Costa, C.D., Kashiwagi, M.B., Mathias, M.H. (2015). Rotor failure detection of induction motors by wavelet transform and Fourier transform in non-stationary condition. Case Studies in Mechanical Systems and Signal Processing, pp. 1-13.

[30] Ribrant, J.; Bertling, L. Survey of Failures in Wind Power Systems with Focus on Swedish Wind Power Plants during 1997–2005. In Proceedings of the 2007 IEEE Power Engineering Society General Meeting, Tampa, FL, USA, 24–28 June 2007; pp. 1–8.

[31] Musial, W, Butterfield, S, & McNiff, B. (2007). Improving wind turbine gearbox reliability. European Wind Energy Conference, pp 1–10.

[32] Kar, C, & Mohanty, A. (2008). Monitoring Gear Vibrations through Motor Current Signature Analysis and Wavelet Transform. Journal of Sound and Vibration, volume 311, pp. 109–132.

[33] M. Blodt, M. Chabert, J. Regnier, and J. Faucher, "Mechanical Load Fault Detection in Induction Motors by Stator Current Time-Frequency Analysis," IEEE Transactions on Industry Applications, vol. 42, no. 6, pp. 1454-1463, 2006.

[34] Cibulka, J, Ebbesen, M.K., Robbersmyr, K.G. (2012). Journal of Physics: Conference Series, volume 364, pp. 1-22.

[35] Ocak.H and Loparo. K (2004), HMM-based fault detection and diagnosis scheme for rolling element bearing, journal of vibration and acoustics.

[36] Li, W, Mechefske, C.K. (2005). Detection of Induction Motor Faults: A Comparison of Stator Current, Vibration and Acoustic Methods. Journal of Vibration and Control, 12(2), pp. 165–188,

[37] Andriamalala, R.N., H. Razik, G. and F.M. Sargos, C.R da Silva and E.R.C da Silva, 2006. IEEE, pp: 2340-2345.

[38] Messaoudi, M, Sbita, L, Abdelkrim, M.N. (2007). Faults Detection in Induction Motor via Stator Current Spectrum Analysis. International Conference on Electrical Engineering Design & Technologies, Hammamet Tunisia, pp. 1-7.

[39] Onel, I.Y., Dalci, K.B., Senol, I. (2005). Detection of bearing defects in three-phase induction motors using Park’s transform and radial basis function neural networks. Sadhana, 31(3), pp. 235-244.

[40] Turk N (2016), Fault Diagnosis of Induction Motor Using MCSA, International Journal of Electrical and Computer Engineering, Volume 8, No. 1, pp 13-18.

[41] Mathew, N.L., & Sharma, A. (2018). Various Indices for Diagnosis of Air-gap Eccentricity Fault in Induction Motor-A Review. 3rd International Conference on Communication Systems, volume 331, pp. 1-10.

[42] Alfadel, B.M.A.A. (2016). Speed Sensorless Control of Induction Motor by Using Model Reference Adaptive System. Dissertation, University of Science and Technology.

[43] Karmakar, S, (2016). Induction Motor Fault Diagnosis. Springer Publications, pp. 7-29.

[44] Prakash, V. (2014). Achieving energy efficiency in three phase induction motors non destructive quality assurance and analysis approaches. Retrieved on 16th August 2019 from http://hdl.handle.net/10603/27176

[45] Valencia, J.B., Puche-Panadero, R, Martinez-Roman, J, Sapena-Bano, A, Pineda-Sanchez, M, Perez-Cruz, J, Riera-Guasp, M. (2018). Automatic Fault Diagnostic System for Induction Motors under Transient Regime Optimized with Expert Systems. Electronics, 8(6), pp. 1-16.

[46] Sapena-Baño A, Pineda-Sanchez, M, Puche-Panadero, R, Perez-Cruz, J, Roger-Folsch, J, Riera-Guasp, M. Martinez-Roman, J. (2015). "Harmonic Order Tracking Analysis: A Novel Method for Fault Diagnosis in Induction Machines," in IEEE Transactions on Energy Conversion, 30(3), pp. 833-841.

[47] Burriel-Valencia, J., Puche-Panadero, R., Martinez-Roman, J., Sapena-Bano, A., Pineda-Sanchez, M., Perez-Cruz, J., & Riera-Guasp, M. (2019). Automatic Fault Diagnostic System for Induction Motors under Transient Regime Optimized with Expert Systems. *Electronics*, *8*(1), 6.

[48] Faiz, J, Takbash, A.M., Mazaheri-Tehrani, E. (2017). A Review of Application of Signal Processing Techniques for Fault Diagnosis of Induction Motors. AUT Journal of Electrical Engineering, 49(2), pp. 109-122

[49] Elbouchikhi, E, Benbouzid, M, & Choqueuse, V. (2015). Induction machine diagnosis using stator current advanced signal processing. International Journal on Energy Conversion, 3(3), pp.76-87.

[50] Singh, K, Choudhury, R.A. (2019). Induction Motor Internal and External Fault Detection. Emerging Research in Electronics, Computer Science and Technology, pp. 1331-1346.

[51] Wang, C, Gan, M, Zhu, C. (2016). A supervised sparsity-based wavelet feature for bearing fault diagnosis. Journal of Intelligent Manufacturing, 30(1), pp. 229-239.

[52] Asgharpour-Alamdari, A, Alinejad-Beromi, Y, Yaghobi, H. (2016). Fuzzy-Based Speed Controller for Improvement of Induction Motor’s Drive Performance. Iranian Journal of Fuzzy Systems, 13(2), pp. 61-70.

[53] Dorjee’s, R.G. (2014). Fuzzy Logic Control of Three Phase Induction Motor Using Rotor Resistance Control Method. International Journal on Recent and Innovation Trends in Computing and Communication, 2(10), pp. 3099-3103.

[54] Sonje, D.M., Kundu, P, Chowdhury, A, (2017). A Novel Approach for Multi Class Fault Diagnosis in Induction Machine Based on Statistical Time Features and Random Forest Classifier. IOP Conf. Series: Materials Science and Engineering, volume 225, pp. 1-11.

[55] Khireddine, M.S., Abdessemed, S.Y., Makhloufi, M.T. (2014). Fault detection and diagnosis in induction motor using artificial intelligence technique. MATEC Web of Conferences, volume 16, pp. 1-4.

[56] Bessam, B, Menacer, A, Boumehraz, M, Cherif, H. (2015). Wavelet transforms and neural network techniques for inter-turn short circuit diagnosis

and location in induction motor. International Journal of System Assurance Engineering and Management, 8(1), pp. 478-488.

[57] Janrao, S, Ambekar, R. (2018). Fault Diagnosis of an Induction Motor Using Motor Current Signature Analysis. International Journal of Applied Engineering Research, 13(12), pp. 11002-1008.

[58] Bhattacharyya, S., Sen, D., Adhvaryyu, S., & Mukherjee, C. (2015). Induction motor fault diagnosis by motor current signature analysis and neural network techniques. *Journal of Advanced Computing and Communication Technologies*, *3*(1), 12-18.

[59] Kathiravan, M, Prakasam, K. (2014). Motor Current Signature Analysis Based Fault Diagnosis of Induction Motor. International Journal of Power Control and Computation(IJPCSC), 6(2), pp. 56-62.

[60] Hamdani, S, Ibtiouen, T.R., Fadel, M. (2011). Neural Network technique for induction motor rotor faults classification –Dynamic eccentricity and broken bar faults. IEEE Publications.

[61] Jose, G, Jose, V. (2013). Fuzzy logic based Fault Diagnosis in Induction Motor. 14th National Conference on Technological Trends, pp. 150-156.

[62] Mohamed, K.A.H., Hassaan, G.A., Hegazy. A.A. (2015). Induction Motor Electrical Fault Diagnosis by a Fundamental Frequency Amplitude using Fuzzy Inference System. International Journal of Recent Engineering Science (IJRES), volume 18, pp. 7-16.

[63] Marcelo, C, Fossatti, J.P., Terra, J.I., (2012). Fault Diagnosis of Induction Motors Based on FFT. Retrieved on 18th August 2019 from http://cdn.intechopen.com/pdfs/35219/InTech-Fault_diagnosis_of_induction_motors_based_on_fft.pdf

[64] Mohammadi, H.R., Akhavan, A. (2014). Parameter Estimation of Three-Phase Induction Motor Using Hybrid of Genetic Algorithm and Particle Swarm Optimization. Journal of Engineering, pp. 1-6.

[65] Wang, J, Gao, R.X., Yan, R. (2011). Broken-Rotor-Bar Diagnosis for Induction Motors. Journal of Physics: Conference Series, volume 305, pp. 1-12.

[66] Zolfaghari, S, Noor, S.B.M.N., Mehrjou, M.R., Marhaban, M.H., Mariun, N. (2017) Broken Rotor Bar Fault Detection and Classification Using Wavelet Packet Signature Analysis Based on Fourier Transform and Multi-Layer Perceptron Neural Network. Applied Sciences, 8(2), pp. 1-21.

[67] Nemec, M, Ambrozic, V, Fiser, R, Nedeljkovi´c, D, Drobniˇc, K. (2017). Induction Motor Broken Rotor Bar Detection Based on Rotor Flux Angle Monitoring. Energies, 12(794), pp. 1-17.

[68] Siddiqui, K.M., Giri, V.K. (2012). Broken rotor bar fault detection in induction motors using Wavelet Transform. IEEE Publications.

[69] Khater, F.M.H., El-Sebah, M.I.A., Osama, M, Sakkoury, S. (2016). Proposed fault diagnostics of a broken rotor bar induction motor fed from PWM inverter. Journal of Electrical Systems and Information Technology, 3(3), pp. 387-397.

[70] Powers, C.S. (2015). Offline Detection of Broken Rotor Bars in Ac Induction Motors. Master Thesis, Colorado State University.

[71] Zhao, Z, Wang, X, Zhang, X. (2015). Fault Diagnosis of Broken Rotor Bars in Squirrel-Cage Induction Motor of Hoister Based on Duffing Oscillator and Multifractal Dimension. Advances in Mechanical Engineering, volume 6.

[72] Filho, L.P.C.M., Baccarini, L.M.R., Batista, F.B., Alves, D.A. (2018). Broken rotor bar detection using empirical demodulation and wavelet transform:

suitable for industrial application. Electrical Engineering, 100(4), pp. 2253–2260.

[73] Cekic, Y, Eren, L. Broken rotor bar detection via four-band wavelet packet decomposition of motor current. Electrical Engineering, 100(3), pp. 1957–1962.

[74] Bessous, N, Zouzou, S.E., Bentrah, W, Sbaa, S, Sahraoui, M. (2018). Diagnosis of bearing defects in induction motors using discrete wavelet transform. International Journal of System Assurance Engineering and Management, 9(2), pp 335–343.

[75] Glowacz, A. (2019)Fault diagnosis of single-phase induction motor based on acoustic signals. Mechanical Systems and Signal Processing, volume 117, pp. 65-80.

[76] Jigyasu, R, Mathew, L, Sharma, A. (2018) Multiple Faults Diagnosis of Induction Motor Using Artificial Neural Network. International Conference on Advanced Informatics for Computing Research, pp. 701-710.

[77] Aimer, A.F., Boudinar, A.H., Benouzza, N, Bendiabdellah, A. (2017). Induction motor bearing faults diagnosis using Root-AR approach: simulation and experimental validation. Electrical Engineering, 100(3), pp 1555–1564.

[78] Eren, L. (2017). Bearing Fault Detection by One-Dimensional Convolutional Neural Networks. Mathematical Problems in Engineering, pp. 1-9.

[79] Glowacz, A, Glowacz, W, Glowacz, Z, Kozik, J. (2017). Early fault diagnosis of bearing and stator faults of the single-phase induction motor using acoustic signals. Measurement, volume 113, pp. 1-9.

[80] Boudinar, A.H., Benouzza, N, Bendiabdellah, A, Khodja, M.E.A. (2016). Induction Motor Bearing Fault Analysis Using a Root-MUSIC Method. IEEE Transactions On Industry Applications, 52(5), pp. 3859-3860.

[81] Singhal, A, Khandeka, M.A. (2013). Bearing Fault Detection in Induction Motor Using Motor Current Signature Analysis. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering, 2(7), pp. 3258-3264.

[82] Kripakaran, P, Reddy, B.R. (2017). Diagnosis of bearing fault in induction motor by zero sequence current. IEEE Publications.

[83] Polat, A, Yilmaz, A, Ergene, L.T. (2018). Investigation of The Effects of Eccentricity on Induction Motor via Multi-Resolution Wavelet Analysis. Electrica, 18(2), pp. 187-197.

[84] Mehala, N, Dahia, R. (2017). Spectral Analysis for Faults Diagnosis of Induction Machines. Retrieved on 19th August 2019 from http://www.iitk.ac.in/npsc/Papers/NPSC2012/papers/12102.pdf

[85] Rouaibia, R, Arbaoui, F, Bahi, T. (2016). Detection of Eccentricity Fault in Closed-Loop Induction Motor Drive using Wavelet Transform. Proceedings of the International Conference on Recent Advances in Electrical Systems, Tunisia, pp. 125-130.

[86] Mirzaeva, G, Saad, K.I., Jahromi, M. G. (2016). Comprehensive Diagnostics of Induction Motor Faults Based on Measurement of Space and Time Dependencies of Air Gap Flux. IEEE Publications.

[87] Halem, N, Zouzou, S.E., Srairi, K, Guedidi, S, Abood, F.A. (2013). Detection of Static Eccentricity Fault In Saturated Induction Motors By Air-Gap Magnetic Flux Signature Analysis Using Finite Element Method. Journal of Fundamental and Applied Sciences, 5(1), pp. 53-68.

[88] Reddy, A.V., Kumar, B. M. (2019). Conditional Monitoring of Switched Reluctance Motor for Static and Dynamic Eccentricity Faults with Fault Isolation. International Journal of Mathematical, Engineering and Management Sciences, 4(3), pp. 671–682.

[89] Yahia, K, Sahraoui, M, Cardoso, M, Ghoggal, A. (2016). The Use of a Modified Prony's Method to Detect the Airgap-Eccentricity Occurrence in Induction Motors. IEEE Publications.

[90] Ojaghi, M, Aghmasheh, R, Sabour, M. (2016). Model-based Exact Technique to Identify Type and Degree of Eccentricity Faults in Induction Motors. IET Electric Power Applications, 10(8), pp. 706 – 713.

[91] Sousa, K.M., Dreyer, U.J., Martelli, C, Silva, J.C.C.D.S. (2016). Dynamic Eccentricity Induced in Induction Motor Detected by Optical Fiber Bragg Grating Strain Sensors. IEEE Publications.

[92] Varghese, S.E., Reema, N. (2016) Effects of Switching Faults on Induction Motor Drive System. International Research Journal of Engineering and Technology (IRJET), 3(5), pp. 607-611.

[93] Sreeja, V, Mini, V.P., Sreedevi, G. (2016) Fault Analysis of Induction Motor Drive System Using Maxwell-Simplorer. International Journal of Electrical, Electronics and Data Communication, 3(9), pp. 4-9.

[94] Gulhane, S.O., Salodkar, M.R. (2016). Review of Detection of Faults in Induction Motor. International Research Journal of Engineering and Technology (IRJET), 3(8), pp. 1771-1774.

[95] Aderiano M. da Silva, Richard J. Povinelli and Nabeel A.O. Demerdash, 2008. Induction Machine Broken Bar and Stator Short-Circuit Fault Diagnostics Based on Three-Phase Stator Current Envelopes "IEEE transaction on industrial electronics, 55(3): 1310-1318.

[96] Fireteanu, V. (2013). Detection of the Short-Circuit Faults in the Stator Winding of Induction Motors based on Harmonics of the Neighboring Magnetic Field. Journal of Physics: Conference Series, volume 450, pp. 1-7.

[97] Bazurto, A.J., Quispe, E.C., Mendoza, R.C. (2016). Causes and Failures Classification of Industrial Electric Motor. Researchgate Publications.

[98] Alwan, H, Sabbagh, Q.S. (2017). Various Types of Faults and Their Detection Techniquesin Three Phase Induction Motors Fault. Researchgate Publications.

[99] Bhavsar R C and Patel R A (2013), Various Techniques for Condition Monitoring of Three Phase Induction Motor- A Review, International Journal of Engineering Inventions, Volume 3, Issue 4, pp 22-26.

[100] Dash, R.N., Sahu, S, Panigrahi, C.K., Subudhi, B. (2016). Condition Monitoring of Induction Motors- A Review. IEEE Publications.

[101] Wang, W, Li, D.D. (2015). Health Condition Monitoring of Induction Motors. Licensee InTech Publications.

[102] Chandralekha, R, Jayanthi, D. (2016) Diagnosis of Faults in Three Phase Induction Motor using Neuro Fuzzy Logic. International Journal of Applied Engineering Research, 11(8), pp 5735-5740.

[103] Bhowmik, P.S., Pradhan, S, Prakash, M. (2013). Fault Diagnostic And Monitoring Methods Of Induction Motor: A Review. International Journal of Applied Control, Electrical and Electronics Engineering (IJACEEE), 1(1), pp. 1-18.

[104] Chang, *et al* (2019). Induction Motors Condition Monitoring System with Fault Diagnosis Using a Hybrid Approach. Energies, 12(1471), pp. 1-12.

[105] Duan, F, Zivanovic, R. (2014). Condition Monitoring of an Induction Motor Stator Windings Via Global Optimization Based on the Hyperbolic Cross Points. IEEE Publications.

[106] Tsypkin, M. (2017). Induction motor condition monitoring: Vibration analysis technique — diagnosis of electromagnetic anomalies. IEEE Publications.

[107] Tsypkin, M. (2013). Induction motor condition monitoring: Vibration analysis technique - a twice line frequency component as a diagnostic tool. IEEE Publications.

[108] Hurtado, Z. M., Tello, C. P., & Sarduy, J. G. (2015). A review on location, detection and fault diagnosis in induction machines. *Journal of Engineering Science & Technology Review*, *8*(3).

[109] Thakur, A., Wadhwani, S., & Sondhiya, V. (2013). Health monitoring of rotating electrical machine using soft computing techniques: A Review. *International Journal of Scientific and Research Publications*, *3*(11), pp 1-3.

[110] Bulent Ayhan, H. Joel Trussell, Mo, Yuen Chow and Myung-Hyun Song, 2008. On the Use of a Lower Sampling Rate for Broken Rotor Bar Detection With DTFT and AR-Based Spectrum Methods" IEEE transaction on industrial electronics, 55(3): 1421-1433.

[111] Chaturvedi, D. K., Iqbal, M. S., & Singh, M. P. (2013, October). Health monitoring techniques of induction motor: an overview. In *4th International Conference on Emerging Trends in Engineering and Technology (IETET-2013) of ACEEE at Geeta Institute of Management and Technology, Kurukshetra, India* (p. 469477).

[112] Agrawal D, Yadav N and Saini S (2015), Condition Monitoring of Slip-ring Induction Motor, International Journal of Innovative Research in Advanced Engineering, Volume 2, Issue 3, pp 78-83.

[113] Parekh K J (2017), Analysis of the Induction Motor used in Temperature Controller Machine by Condition Based Monitoring System, International Journal of Science Technology and Engineering, Volume 3, Issue 10, pp 154-161.

[114] Ojaghi, M., Sabouri, M., & Faiz, J. (2014). Diagnosis methods for stator winding faults in three-phase squirrel-cage induction motors. *International transactions on electrical energy systems*, *24*(6), pp 891-912.

[115] Karmakar, S., Chattopadhyay, S., Mitra, M., & Sengupta, S. (2016). *Induction motor fault diagnosis* (Vol. 25). Springer.

[116] Glowacz, A., & Glowacz, Z. (2016). Diagnostics of stator faults of the single-phase induction motor using thermal images, MoASoS and selected classifiers. *Measurement*, *93*, 86-93.

[117] Baneira, F., Yepes, A. G., López, Ó., & Doval-Gandoy, J. (2015). Estimation method of stator winding temperature for dual three-phase machines based on dc-signal injection. *IEEE Transactions on Power Electronics*, *31*(7), pp 5141-5148.

[118] Rao R D G and Aprameya K S (2018), Monitoring Of Inter-Turn Insulation Degradation In Induction Motor Using Spirit Thermometer And Integrated Programmable Platform, International Journal of Research in Advent Technology, Special Issue.

[119] Chaudhary M, Nishanth and Danish N (2015), Vibration Monitoring of Induction Motor by Using Accelerometer, International Journal of Scientific Research Engineering and Technology, Volume 4, Issue 8, pp 850-852.

[120] Riera-Guasp, M.; Cabanas, M.F.; Antonino-Daviu, J.A.; Pineda-Sanchez, M.; Garcia, C.H.R., "Influence of non consecutive bar breakages in motor current signature analysis, for the diagnosis of rotor faults in induction motors, IEEE Transactions on Energy Conversion, Vol. 25, Issue 1 , pp 80-89, 2010.

[121] Kumar, T. C. A., Singh, G., & Naikan, V. (2015). Effectiveness of vibration monitoring in the health assessment of induction motor. *International Journal of Prognostics and Health Management*, *6*(Special Issue Uncertainty in PHM) 007), pp 1-9.

[122] Kumar, S. S., & Ashok, S. D. (2014). Development of acoustic emission and motor current based Fuzzy Logic model for monitoring weld strength and nugget hardness of FSW joints. *Procedia Engineering*, *97*, pp 909-917.

[123] San-Um W and Lotrakul P (2014), The Contactless Real Time Monitoring of a Single Phase Induction Motor Using Acoustic Emission Sensor, Management of Innovation Technology International Conference, pp 44-48.

[124] Islam, M. R., Uddin, J., & Kim, J. M. (2016). Acoustic Emission Sensor Network Based Fault Diagnosis of Induction Motors Using a Gabor Filter and Multiclass Support Vector Machines. *Adhoc & Sensor Wireless Networks*, *34*.

[125] Gopal et.al 2018, Enhancing the performance of motor imagery classification to design a robust brain computer interface using feed forward back-propagation neural network

[126] Patil A V and Kumar B (2013), An Extensive Review of Momentous Researches on Acoustic Emission and Vibration, International Journal of Modern Engineering Research, Volume 3, Issue 6, pp 3564-3567.

[127] Ferrando Chacon, J. L., Andicoberry, E. A., Kappatos, V., Papaelias, M., Selcuk, C., & Gan, T. H. (2016). An experimental study on the applicability of acoustic emission for wind turbine gearbox health diagnosis. *Journal of Low Frequency Noise, Vibration and Active Control*, *35*(1), 64-76.

[128] Bilal Akin, Umut Orguner, Hamid A. Toliyat and Mark Rayner, 2008. Low Order PWM Inverter Harmonics Contributions to the Inverter-Fed Induction Machine Fault Diagnosis" Industrial Electronics, IEEE Transactions on Feb. 2008, 55(2): 610-619

[129] Nistor C G, Scutaru G, Campeanu R and Cernat M (2015), Noise and Vibration Monitoring for Premium Efficiency IE 3 Three-Phase Induction Motors, Advances in Electrical and Computer Engineering, 15 (3), pp 117-122.

[130] Kurien, C., & Srivastava, A. K. (2018). Condition monitoring of systems in thermal power plant for vibration, motor signature, noise and wear debris analysis. *World Scientific News*, *91*, pp 31-43.

[131] Goyal, D., Chaudhary, A., Dang, R. K., Pabla, B. S., & Dhami, S. S. (2018). Condition Monitoring of Rotating Machines: A Review. *World Scientific News*, *113*, 98-108.

[132] Van Hecke, B. E. (2015). *Development of Novel Acoustic Emission Based Methodology and Tools for Bearing Fault Diagnostics* (Doctoral dissertation).

[133] Misra, R., Moradabad, M. I. T., & Agarwal, A. (2015). Condition monitoring and fault diagnosis in induction motor: case study. *MIT Int. J. Electr. Instrum. Eng.*, *5*(1), pp 33-35.

[134] Çalis, H. (2014). Vibration and motor current analysis of induction motors to diagnose mechanical faults. *Journal of Measurements in Engineering*, *2*(4), pp 190-198.

[135] Mallya M (2013), Condition Monitoring and Fault Diagnosis of Induction Motors, (Doctoral dissertation, Anna University, Chennai).

[136] Indraprassad G T, Sakthivel E, Ramesh J, Janarthanan R, Bagyalakshmi R and Kamesh G (2014), Fuzzy Logic based Health Monitoring of Induction Machine using Lab view, International Journal of Scientific and Engineering Research, Volume 5, Issue 3, pp 954-959.

[137] Khalaf F M (2017), Advance Current Monitoring Techniques to Detect and Diagnosis the Inter-Turn Stator Fault in Three Phase Induction Motor, International Journal of Engineering and Science, Volume 6, Issue 1, pp 66-70.

[138] Jaksch, I., Schreiber, R., & Fuchs, P. (2015, June). The analysis of induction motor electromagnetic field and shaft revolution oscillations at dynamic rotor faults. In *2015 IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM)* (pp. 1-6).

[139] Kumar, P., & Isha, T. B. (2016, December). Electromagnetic field analysis of 3-Phase induction motor drive under broken rotor bar fault condition using FEM. In *2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)* (pp. 1-6).

[140] Billard T, Lebey T and Fresnet F (2014), Partial discharge in electric motor fed by a PWM inverter: off-line and on-line detection, IEEE Transactions on Dielectrics and Electrical Insulation, Volume 21, Issue 3.

[141] Haddadnia, J, Seryasat, O.R., Rabiee, H, Zade, H.G. (2014). Fault Detection of Induction Motor Ball Bearings. Advances in Environmental Biology, 8(6), pp. 1802-1809

[142] Stone, G. C., Sedding, H. G., & Chan, C. (2017). Experience With Online Partial-Discharge Measurement in High-Voltage Inverter-Fed Motors. *IEEE Transactions on Industry Applications*, *54*(1), 866-872.

[143] Renuka H B (2017), Detection of Partial Discharge Activity in H.V Rotating Equipment, IJSRSET, Volume 3, Issue 1, pp 140-143.

[144] Tripathi A and Asati N (2013), Artificial Neural Network Controller for Induction Motor Drive, International Journal of Science and Research, Volume 4, Issue 6, pp 805-212.

[145] Hussain, S., & Bazaz, M. A. (2016). Neural network observer design for sensorless control of induction motor drive. *IFAC-PapersOnLine*, *49*(1), pp 106-111.

[146] Omjeh B A, Idoniboyeobu D and Ajabuego G O (2015), Artificial Neural Network Based Induction Motor Speed Controller, International Journal of Electronics Communication and Computer Engineering, Volume 6, Issue 1, pp 1-5.

[147] Pyne, M., Chatterjee, A., & Dasgupta, S. (2014). Speed estimation of three phase induction motor using artificial neural network. *International Journal of Energy and Power Engineering*, *3*(2), pp 52-56.

[148] Delgado-Arredondo, P.A.; Morinigo-Sotelo, D.; Osornio-Rios, R.A.; Avina-Cervantes, J.G.; Rostro-Gonzalez, H.; Romero-Troncoso, R.D. Methodology for fault detection in induction motors via sound and vibration signals. Mech. Syst. Signal Process. 2017, 83, 568–589

[149] Kanović, Ž., Matić, D., Jeličić, Z., & Petković, M. (2013). Induction motor fault diagnosis based on vibration analysis: A case study. *Journal on Processing and Energy in Agriculture*, *17*(1), 47-50.

[150] Tipirdamaz C (2017), Vibration Analysis for Induction Motors with an Expert System, Master of Science Thesis.

[151] Pandey, V. P., & Choudhary, P. K. (2013). Induction motor condition monitoring using fuzzy logic. *Advance in Electronic and Electric Engineering*, *3*(6), pp 755-764.

[152] Samanta, S., Seal, P., Bera, J. N., & MCKVIE, L. (2017). Condition monitoring of single phase induction motor using fuzzy logic scheme. *AMSE J-AMSE IIETA Publication-2017-Series,*, *38*, 80-88.

[153] Patni Y R and Ansari M M (2018), Modelling & Condition Monitoring of 3**ϕ** Induction Motor using Fuzzy Logic, International Research Journal of Engineering and Technology, Volume 5, Issue 10, pp 285-292.

[154] Rajpoot S C, Soni N K, Shrivastaba S and Rajpoot P S (2018), Speed Control of Three Phase Motor Using Fuzzt Logic Controller, International Research Journal of Engineering and Technology, Volume 5, Issue 10, pp 478-485.

[155] Soni N K, Shrivastava S and Dubey M (2018), Speed Control of Induction Motor Using Fuzzy LogicL A review, International Journal of Science, Engineering and Technology Research, Volume 7, Issue 10, pp 758-760.

[156] Sivaraju S S, Devarajan N and Ferreira F J T E (2013), Performance improvement of Induction motor by using Particle Swarm Optimization, Journal of Electrical Engineering, 13 (1), pp 112-116.

[157] Luo, Y. C., & Huang, W. A. (2019). Sensorless rotor field direct orientation controlled induction motor drive with particle swarm optimization algorithm flux observer. *Journal of Low Frequency Noise, Vibration and Active Control*, *38*(2), pp 692-705.

[158] Elkholy M M and Elhameed M A (2015), Braking of Three Phase Induction Motorsby Controlling Applied Voltage and Frequency Based on Particle Swarm Optimization Technique, International Journal of Power Electronics and Drive System, Volume 5, No. 4, pp 520-528.

[159] Barusu, M.R., Sethurajan, U, Deivasigamani, M. (2019). Diagnosis of Bearing Outer Race Faults Using a Low-Cost Non-Contact Method with Advanced Wavelet Transforms. Elektronika Ir Elektrotechnika, 25(1), pp. 44-53.

[160] Tripati, J.S., Agrawal, J.F. (2018). Vibration Analysis of Ball Bearings with Outer Race Defects: Development of Mathematical Model and Experimental Validation. International Journal on Recent Technologies in Mechanical and Electrical Engineering (IJRMEE), 5(4), pp. 16-22.

[161] Iorgulescu, M. (2010). Study Relation between Fault Noise In Electric Motor. International Journal on "Technical and Physical Problems of Engineering" (IJTPE), 2(4), pp. 69-73.

[162] Hongrui, C, Linkai, N , Zhengjia, H. (2012). Method for Vibration Response Simulation and Sensor Placement Optimization of a Machine Tool Spindle System with a Bearing Defect", Sensors, volume 12, pp. 8732-8754.

[163] Nabhan, A, Nouby, M, Sami, A.M., Mousa, M.O. (2015). Bearing Fault Detection Techniques - A Review. Turkish Journal of Engineering, Sciences and Technology

[164] Wang, L. (2007). Induction Motor Bearing Fault Detection Using A Sensorless Approach. PhD Thesis, Texas A&M University.

[165] Mustafa, M.O. (2015). On Fault Detection, Diagnosis and Monitoring for Induction Motors. PhD Thesis, Luleå University of Technology.

[166] Kumar, D.D. (2010). Block diagram of Induction motor fault categories. As Cited in Kumar, D.D. (2010). An investigation into fault diagnosis of induction motor by artificial intelligent technique. Retrieved on 13th August 2019 from http://hdl.handle.net/10603/174822

[167] Dekys, V. (2017). Condition monitoring and fault diagnosis. Procedia Engineering, volume 177, pp. 502 – 509.

[168] Finley, W.R. (n.d) Troubleshooting Induction Motors. Retrieved on 25th August 2019 from https://www.industry.usa.siemens.com/drives/us/en/electric-motor/anema-motors/Documents/trouble-shooting-induction-motors.pdf

[169] Singh, S, Kumar, A, Kumar, N. (2014). Motor Current Signature Analysis for Bearing Fault Detection in Mechanical Systems. Procedia Materials Science, volume 6, pp. 171 – 177.

[170] Cardoso, A. J. M., Drif, M. (2008). "Airgap Eccentricity Fault Diagnosis in Three- Phase Induction Motors by the Complex Apparent Power Signature Analysis," IEEE Transactions on Industrial Applications, 55(3), pp. 18–22.

[171] Stief, A.; Ottewill, J.R.; Orkisz, M.; Baranowski, J. Two Stage Data Fusion of Acoustic, Electric and Vibration Signals for Diagnosing Faults in Induction Motors. Elektronika ir Elektrotechnika 2017, 23, 19–24.

[172] Xia, K.; Li, Z.R.; Lu, J.; Dong, B.; Bi, C. Acoustic Noise of Brushless DC Motors Induced by Electromagnetic Torque Ripple. J. Power Electron. 2017, 17, 963–971

[173] Uekita, M.; Takaya, Y. Tool condition monitoring for form milling of large parts by combining spindle motor current and acoustic emission signals. Int. J. Adv. Manuf. Technol. 2017, 89, 65–75.

[174] Tian, K, Zhang, T, Ai, Y, Zhang, W. (2018). Induction Motors Dynamic Eccentricity Fault Diagnosis Based on the Combined Use of WPD and EMD-Simulation Study. Appl. Sci. 8(170), pp. 1-15.

[175] Alwan, H.O., Farhan, N.M., S-Al-Sabbagh, Q. (2017). Detection of Static Air-Gap Eccentricity in Three Phase induction Motor by Using Artificial Neural Network (ANN). Int. Journal of Engineering Research and Application, 7(5), pp.15-23.

[176] Mehala, N, Dahiya, R. (2007). Motor Current Signature Analysis and its Applications in Induction Motor Fault Diagnosis. International Journal Of Systems Applications, Engineering & Development, 2(1), pp. 29-35.

[177] Jeevanand, S, Singh, B, Panigrahi, B.K., & Negi, V. (2010). State of Art on Condition Monitoring of Induction Motors. IEEE Publications.

[178] Agarwal, D, Yadav, N, Saini, S. (2015). Condition Monitoring of Slip-ring Induction Motor. International Journal of Innovative Research in Advanced Engineering (IJIRAE), 3(2), pp. 78-84.

[179] Siljak, H.; Subasi, A. Berthil cepstrum: A novel vibration analysis method based on marginal Hilbert spectrum applied to artificial motor aging. Electr. Eng. 2018, 100, 1039–1046

[180] Ghoggal A., Zouzou S.E., Razik H., Sahraoui M., Khezzar A., (2009). An improved model of induction motors for diagnosis purposes – Slot skewing effect and air–gap eccentricity faults‖, Energy Conversion and Management, 50(5), pp. 1336–1347.

[181] Iqbal, S. (2013). Health Monitoring System for Three Phase Induction Motor using Soft Computing Techniques. PhD Thesis, Dayalbagh Educational Institute.

[182] Fischer, K, Coronado, D.A. (2015). Condition Monitoring of Wind Turbines: State of the Art, User Experience and Recommendation; Fraunhofer Institute for Wind Energy and Energy System Technology IWES: Bremerhaven, Germany, pp. 51–56.

[183] Chang, H.C., Jheng, Y.M., Kuo, C.C., Hsueh, Y.M. (2015). Induction Motors Condition Monitoring System with Fault Diagnosis Using a Hybrid Approach. Energies, 12(1471), pp. 1-12.

[184] Irfan, M, Saad, N, Ibrahim, R, Asirvadam, V.S., Alwadie, A.S., Sheikh, M.A. (2017). An Assessment on the Non-Invasive Methods for Condition Monitoring of Induction Motors. Licensee InTech Publications.

[185] Pezzani C, Donolo P, Bossio G, Donolo M, Guzman A and Zocholl S E (2013), Detecting Broken Rotor Bars with Zero Setting Protection, Available https://www.eiseverywhere.com/file_uploads/218d988d5b6d8695a4e31a87a82d0c81_don_pap.pdf, accessed on 24th August 2019.

[186] Dogruer T and Akar M (2016), Broken Rotor Bar Fault Diagnosis in Induction Motors using Resampling Based Order Tracking Analysis Method, Journal of New Results in Science, No. 12, pp 111-125.

[187] Amr Saleh, Mario Pacas, Adel Shaltout, 2006. Fault Tolerant Field Oriented Control of the Induction Motor for Loss of One Inverter Phase "IEEE, 1-4244-0136-4/06.

[188] Sanap K R, Paraskar S R and Jadhao S S (2017), Broken Rotor Bar Fault Diagnosis of Induction Motor by Signal Processing Techniques, International Journal of Electrical Engineering and Technology, Volume 8, Issue 1, pp 57-67.

[189] Hans M R, Mane P D, Jadhav A D and Jogi V (2018), Protection of Single Phase Induction Motor from Broken Rotor Bar and Thermal Overload, International Journal of Electrical and Computer Engineering, Volume 10, Number 1, pp 1-8.

[190] Dewangan, P., Singh, D., & Sharma, D. (2015), Rotor Side Fault Diagnosis for Induction Motor Using Fuzzy Based Controlled Identifier, *Int. J. Adv. Engg. Res. Studies/IV/II/Jan.-March*, *331*, 332.

[191] Rajagopal B and Singaravelu S (2015), Detection of Broken Rotor Bar Fault of Three Phase Induction Motor by Fast Fourier Transform Using ARM Microcontroller, International Science Press, Volume 8, Issue 2, pp 487-498.

[192] Ameid, T., Menacer, A., Talhaoui, H., & Harzelli, I. (2017). Broken rotor bar fault diagnosis using fast Fourier transform applied to field-oriented control induction machine: simulation and experimental study. *The International Journal of Advanced Manufacturing Technology*, *92*(1-4), pp 917-928.

[193] Goutam S and Thakur A (2017), A Survey on different Rotor Fault Detection Methods for Induction Motor, International Journal of Engineering and Management Research, Volume 7, Issue 3, pp 175-180.

[194] Kraikitrat K and Ruangsinchaiwanich S (2018), Detection and Classification of Rotor Broken Bar Faults in Induction Motor Using Fuzzy Logic and Artificial Neural Networks, Volume 13, No. 2.

[195] Aimer F A, Boudinar A H and Bendiabdellah A (2013), Use of the Short Time Fourier Transform for Induction Motor Broken Bars Detection, International Review on Modelling and Simulations, Volume 6, No. 6, pp

[196] Siddiqui K, Sahay K and Giri V K (2015), Rotor Broken Bar Fault Detection in Induction Motor Using Transformative Techniques, Journal of Electrical Engineering, Volume 15, Issue 1, pp 1-7.

[197] Ayon-Sicaeros, R. A., Cabal-Yepez, E., Ledesma-Carrillo, L. M., & Hernandez-Gomez, G. (2019, March). Broken-Rotor-Bar Detection Through STFT and Windowing Functions. In *2019 IEEE Sensors Applications Symposium (SAS)* (pp. 1-5).

[198] Wang Z, Yang J, Li H, Zhen D, Xu Y and Gu F (2019), Fault Identification of Broken Rotor Bars in Induction Motors Using an Improved Cyclic Modulation Spectral Analysis, Energies, 12 (17).

[199] Shi, P., Chen, Z., & Vagapov, Y. (2013). Wavelet transform based broken rotor-bar fault detection and diagnosis performance evaluations. *International Journal of Computer Applications*, *69*(14).

[200] Mohanty S and Mohanry S K (2014), Broken Rotor Bar Fault Detection using Wavlet, International Journal of Innovations in Engineering and Technology, Volume 4, Issue 1, pp 72-79.

[201] Prainetr, S.; Wangnippanto, S.; Tunyasirut, S. Detection Mechanical Fault of Induction Motor Using Harmonic Current and Sound Acoustic. In Proceedings of the 2017 International Electrical Engineering Congress (iEECON), Pattaya, Thailand, 8–10 March 2017

[202] Granda, D., Aviles, D. A., & Sotomayor, D. (2018). Analysis of signal processing techniques commonly used for broken bars detection on induction motors. *CienciAmérica: Revista de divulgación científica de la Universidad Tecnológica Indoamérica*, *7*(1), pp 60-72.

[203] Kumar K V, Achenkunju A, Mathew J and Mathew A (2018), Investigation of Fast Fourier Transform and Wavelet Transform Approach in Electrical Machines, International Journal of Pure and Applied Mathematics, Volume 118, No. 11, pp 21-27.

[204] Mohamed M A, Sayed M A, Abdelhameed E H and Hassan M A M (2014), Detection and Classification of Broken Rotor Bars Faults in Induction Motor Using Adaptive Neuro-Fuzzy Inference System, MEPCON.

[205] Bessam, B., Menacer, A., Boumehraz, M., & Cherif, H. (2015). DWT and Hilbert transform for broken rotor bar fault diagnosis in induction machine at low load. *Energy Procedia*, *74*, pp 1248-1257.

[206] Liu, D., & Lu, D. (2015). Off-the-grid compressive sensing for broken-rotor-bar fault detection in squirrel-cage induction motors. *IFAC-PapersOnLine*, *48*(21), pp 1451-1456.

[207] Morinigo-Sotelo, D., Romero-Troncoso, R. J., Antonino-Daviu, J. A., & Gyftakis, K. N. (2016, September). Reliable detection of broken rotor bars in induction motors via MUSIC and ZSC methods. In *2016 XXII International Conference on Electrical Machines (ICEM)* (pp. 2881-2886).

[208] Khiam, A., Ngote, N., & Ouassaid, M. (2018), A hybrid TSA-fuzzy logic approach to detect induction motor rotor faults. In *2018 19th IEEE Mediterranean Electrotechnical Conference (MELECON)* (pp. 254-259).

[209] T. Kidar, M. Thomas, and M. Badaoui. Diagnosis of gear faults by cyclostationarity analysis. pages 1–7, 2013.

[210] Frini, M, Soualhi, A, Badaoui, M.E., Marrakchi, G. (2016) Gear Fault Detection Using the Geometric Properties of Electrical Currents in Three-Phase Induction Motor-Based Systems. International Journal of Condition Monitoring, pp. 1-13.

[211] Yadav et al., 2016, Optimal energy control of three phase induction motor drives.

[212] Kia, S.H., Henao, H, Capolino, G.A. (2009). "Analytical and experimental study of gearbox mechanical effect on the induction machine stator current signature," IEEE Trans. Ind. Appl, 45(4), pp. 1405–1415.

[213] Gritli, Y, Bellini, A, Rossi, C, Casadei, D, Filippetti, F, Capolino, G.A. (2017). Condition Monitoring of Mechanical Faults in Induction Machines from Electrical Signatures: Review of Different Techniques. IEEE Publications.

[214] Gangsar, P.; Tiwari, R. Analysis of Time, Frequency and Wavelet Based Features of Vibration and Current Signals for Fault Diagnosis of Induction Motors Using SVM. In Proceedings of the ASME Gas Turbine India Conference, Bangalore, India, 7–8 December 2017.

[215] Kim, K.S., Choa, Y.H., Hong, S.K. (2017). Geared induction motor fault diagnosis by current, noise and vibration considering measurement environment. Journal of International Council on Electrical Engineering, 7(1), pp. 15-21.

[216] Binojkumar, A.C.; Saritha, B.; Narayanan, G. Experimental Comparison of Conventional and Bus-Clamping PWM Methods Based on Electrical and Acoustic Noise Spectra of Induction Motor Drives. IEEE Trans. Ind. Appl. 2016, 52, 4061–407

[217] Tuma, J. (2009). Gearbox noise and vibration prediction and control. Int. J. Acoust. Vib, volume 14, pp. 99–110.

[218] Qu, Y, He, D, Yoon, J, Hecke, B.V., Bechhoefer, E, Zhu, J. (2014). Gearbox Tooth Cut Fault Diagnostics Using Acoustic Emission and Vibration Sensors — A Comparative Study. Sensors, volume 14, pp. 1372-1393.

[219] Vigneshkumar, S, Shankar, V.K., Prakash, N.K., Supriya, P. (2018). Fault Detection in Gearbox using Motor Electrical Signature Analysis. IEEE Publications.

[220] Henao, H. (2014). “Trends in fault diagnosis for electrical machines: A review of diagnostic techniques,” IEEE Ind. Electron. Mag, 8(2), pp. 31–42.

[221] Ottewill, J.R., Orkisz, M. (2013). "Condition Monitoring of Gearboxes Using Synchronously Averaged Electric Motor Signals," Mech. Syst. & Sig. Process.

[222] Moosavian, A.; Najafi, G.; Ghobadian, B.; Mirsalim, M. The effect of piston scratching fault on the vibration behavior of an IC engine. Appl. Acoust. 2017, 126, 91–100

[223] Kumar, N. (2009). Experimental Investigation of Faulty Gearbox Using Motor Current Signature Analysis. Dissertation, National Institute of Technology, Rourkela.

[224] Wajdi, S, Khaled, J. (2019). Induction machine-Gearbox compound tooth fault diagnosis using Hilbert spectrum. Researchgate Publications.

[225] N. Mehala, Current Signature Analysis for Condition Monitoring of Motors, Int. Journal of Electronics and Computer Science Engineering, Vol. 1, No. 3, 2013

[226] Tian, Z, Zuo, J.M., & Wu, S. (2012). Crack propagation assessment for spur gears using modelbased analysis and simulation, Journal of intelligent Manufacturing, 23(2), pp. 239- 253.

[227] Randall, .R.B. (2011). Vibration-based condition monitoring: industrial, aerospace and automotive applications, John Wiley & Sons, pp. 289.

[228] Ki-Seok Kim, Yong-Ho Cho & Sun-Ki Hong, Geared induction motor fault diagnosis by current, noise and vibration considering measurement environment, Journal of International Council on Electrical Engineering, 2017 VOL. 7, NO. 1, 15–21

[229] Kennedy, J., and Eberhart, R.C. 1995. Particle Swarm Optimization. Proc. IEEE Int. Conf. Neural Networks. 4, 1942-48.

LIST OF PUBLICATIONS

Sr. No.	Title of Paper	Name of the Journal where published	Volume & Issue	Year	Pages
1	Health monitoring of induction motors through embedded systems-simulation of broken rotor bar fault and abnormal gear teeth fault.	Microprocessors and Microsystems (SCI) ISSN No. 0141-9331	Volume 76	2020	1-12
2	Condition Monitoring of Induction Motors Through Simulation of Bearing Fault and Air Gap Eccentricity Fault	International Journal of Recent Technology and Engineering (Scopus Indexed) ISSN No. 2277-3878	Volume 8, Issue 3	2019	176-193
3	Brief Review of Fault Detection and Classification in Induction Motor,	Journal of Experimental & Applied Mechanics ISSN No. 2321-516X (Print)	Volume 10, Issue 1	2019	1-6
4	An effectual review on fault detection and classification in Induction Motor	International Refereed Journal of Reviews and Research ISSN No. 2348-2001	Volume 6, Issue 2	2018	41-49
5	A novel and performance aware approach for Induction motor parameter recognition using PSO	International Refereed Journal of Reviews and Research ISSN No. 2348-2001	Volume 6 , Issue 3	2018	11-49
6	Magnetic field analysis for health monitoring of Induction motor using search coil: An empirical review and analysis	International Journal of Computing and Corporate Research ISSN No. 2249-0546	Volume 3, Issue 1	2013	1-12

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