1
Introduction

1.1 INDUCTION MOTOR

Induction motors are considered as the workhorse of the industry owing to its advantageous features such as self-starting, low cost, high efficiency, ruggedness, small size, simple construction, easy speed regulation and low maintenance electromechanical energy conversion. Their applications are found in electrical utility industries, mining industries, petrochemical and many domestic applications. They are also used under pulsating load torque conditions such as in mills, load elevators, electric-powered vehicles, and reciprocating compressors. Other examples include pumps, blowers, fans etc. The full load efficiency of induction motors is around 85-97%. It consumes approximately 50% of the total generated power of an industrialized nation [Thomson and Morrison, 2002]. If the supply voltage and frequency remain constant, then the motor can deliver constant speed, thus is also called constant speed drive. The capacity of the motor ranges from few watts to megawatts which is compliant to the requirement of domestic and industrial purposes. Figure 1.1 shows a typical induction motor. The construction of an induction motor is simple and rugged. It comprises of two major parts, 1) stationary part, and 2) rotating part. The stationary part of the motor is called the stator and the rotating part is called the rotor. Due to the electromagnetic induction principle, a rotating magnetic field is generated when three-phase stator currents flow in the stator windings. This induces voltage in the short-circuited rotor which produces rotor magnetic field. A torque is experienced by the rotor experiences torque with which the rotor starts rotating. Induction motor converts electrical to mechanical energy while vice-versa is true for induction generator. The major parts of the induction motor are described briefly as follows:

Stator- Stator, shown in Figure 1.2 consists of (a) stator frame, (b) stator core, and (c) stator windings. The frame is the outer cylindrical part made up of cast iron or cast aluminium which fits in the stator core inside it. It provides support to the stator core, windings and protects it from the outer environment. The stator core is the stack of high graded cylindrical alloy steel laminations consisting of slots to accommodate the windings. These insulated laminations reduce the eddy

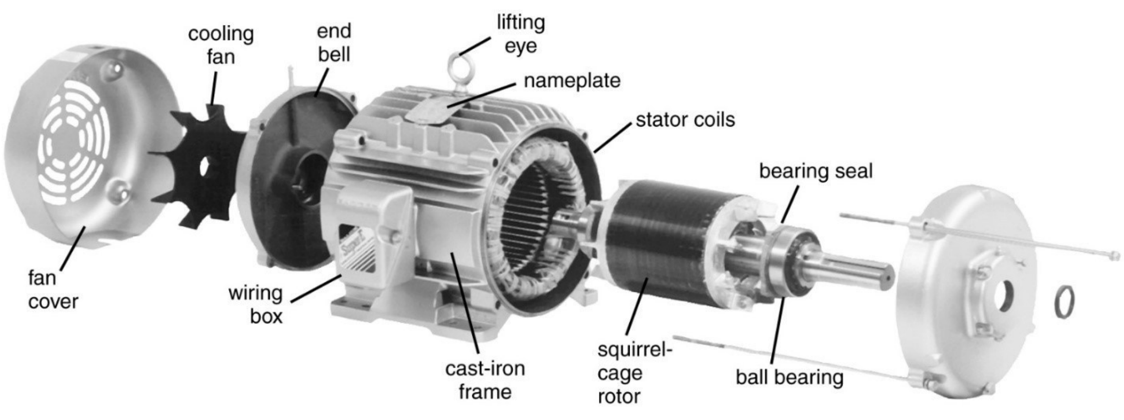

Figure 1.1 : An induction motor

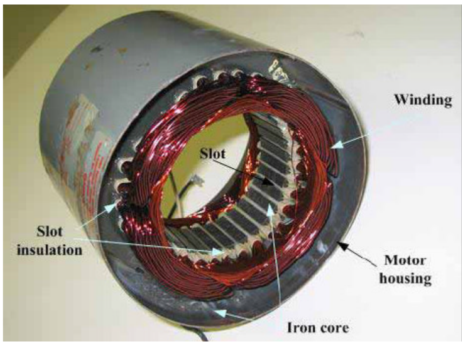

Figure 1.2 : A stator with stator windings

current losses. These laminations are made up of silicon steel to reduce the hysteresis losses. Stator windings are a set of three-phase windings which are 120 degrees electrically apart from each other. The windings are excited using the three-phase supply to produce rotating magnetic flux in the air-gap between the stator and the rotor space. This flux is later used in electromagnetic induction of currents in the rotor through which the rotor rotates at speed less than the synchronous speed.

Rotor- There are two types rotor in an induction motor 1) Squirrel cage rotor, and 2) Wound rotor. Squirrel cage rotor shown in Figure 1.3 is of cylindrical structure with slots on its periphery, this structure is made-up of a stack of steel laminations which are clamped together. These are of cast construction type made up using aluminium or its alloy which is filled up in the slots. This rotor is placed inside the stator core with a small air-gap between the core and the rotor. The current flows through these aluminium bars which are shorted at the end rings. These bars are skewed to avoid magnetic locking between the stator and the rotor. In wound-rotors, a three-phase winding is wound on the rotor and connected to three slip rings which are further connected to external resistances. This helps in reducing the starting current and thus higher torque in the motor. The bearings are used at both ends of the rotor shaft to support the rotor movement without friction.

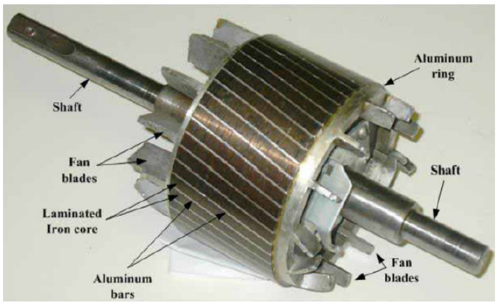

Figure 1.3 : A squirrel cage rotor

Figure 1.4 : A ball-bearing

A ball-bearing shown in Figure 1.4 supports the rotating shaft, hold the rotor in a fixed position such that it can rotate freely with reduced friction. Other parts include end-plates which support the rotor in between stator core; the bearings to support the rotor, the shaft made up of steel used to provide required torque to the load, cooling fan to cool down the heat dissipated during torque production and the terminal box where the three-phase winding terminals are taken out along with ground terminal. The features/characteristics of an induction motor (IM) are listed as follows:

1. **Low cost**: Squirrel cage induction motors are simple, rugged in construction and cheaper in cost due to the absence of other components such as brushes, commutators, and slip rings.
2. **Low maintenance cost**: They require very low maintenance, unlike DC motors and synchronous motors. It has a simple construction catering to ease and cost-effective maintenance
3. **Ease of operation**: Due to the electromagnetic induction principle, the working of an induction motor is effortless. Rotor is not connected to any external electrical supply power. Current induced is due to the low resistance in the rotor which make IM as a self-start motor. Consequently, this reduces the cost and need for maintenance.
4. **Speed Variation**: Induction motors are called as constant-speed motors. Their speed does not vary much from no-load speed to full-load speed.
5. **Durability**: Another advantage is durability which helps the motor to withstand pressure and harsh working conditions for long runs with low cost and maintenance.
6. **Efficiency**: It is a highly efficient motor. The efficiency varies from 85 to 97%.
7. **Robust**: There are no commutating brushes in an induction motor which causes no sparks in the motor. Thus, it can be used in polluted and hazardous environment.

Despite several advantageous features in IM, there are certain disadvantages which are listed below:

1. Three-phase induction motors have a high starting current and poor starting torque. Therefore these motors cannot be used for applications that require high starting torques.
2. The three-phase induction motor is constant speed motor. The change in speed of the motor is very low during different loading conditions. So, the speed control of the motor is tricky.
3. During light load condition, it operates at a low power factor. Because of this, it draws higher current, which results in higher copper loss and less efficiency.

1.2 FAULTS IN INDUCTION MOTOR, THEIR CAUSES AND CONSEQUENCES

Despite its high popularity due to the impermeable construction, the performance of the induction motor is immensely affected by factors such as working environment stresses, thermal conditions, ageing effects, heavy-duty cycles, installation problems, manufacturing defects, loading effects, supply voltage variations, overloading, frequency start/stop, insufficient cooling etc. These stresses lead to the development of incipient faults that are non-detectable directly owing to the low sensitivity of protection systems. Incipient faults do not directly affect the motor's operation, however, in the long run they can converge into major faults leading to complete shut-down which leads to catastrophic downtime. This induces high financial loss and sometimes a risk of human lives. Hence, an early detection of the incipient faults is essential to prevent the same. Thus, effective condition monitoring and fault diagnosis mechanisms are needed to detect incipient faults at an early stage.

The incipient faults are developed in the stator (windings and its core), rotor (bars and end rings), bearings and other faults such as misalignment and eccentricity in the rotor also exist. In general, the majority of faults arise from stator, bearings and the rotor. Figure 1.5 illustrates the broad classification of faults in an induction motor. The major faults in the IM fall in following categories:

1. Bearing faults

Table 1.1 : Percentage sharing of major induction motor faults by two surveys

Fault category	IEEE-IAS (%)	EPRI (%)
Bearing faults	44	41
Stator faults	26	36
Rotor faults	8	9
Others	22	14

2. Stator faults
3. Rotor faults

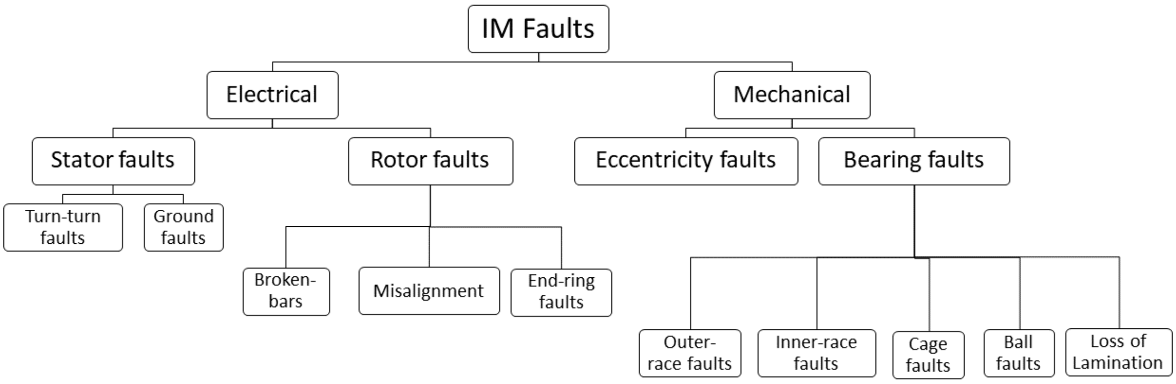

Figure 1.5 : Categories of faults in the induction motor

According to the survey published in IEEE and EPRI [Thorsen and Dalva, 1995; Group et al., 1987], the bearing faults share the largest percentage of faults in IM i.e. 40-50%, followed by stator faults with 30-40% share, the rotor faults with 8-9% share and lastly miscellaneous causes. Table 1.1 gives the percentage sharing of these faults in the surveys, Figure 1.6 gives a pictorial representation of an approximate sharing of all fault as a pie-chart. These studies are utilized so far to consolidate the types and shares of each fault of the motor. These three kinds of faults are taken into consideration in this thesis. The types of faults along with their causes are discussed in the following subsections.

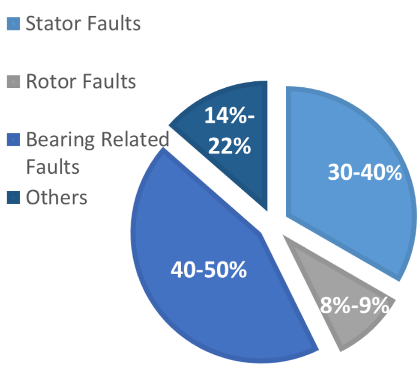

Figure 1.6 : Types of faults in the induction motor

1.2.1 Bearing faults

Bearing faults are the major contributor of faults with 40% share in total motor faults. A bearing has a number of balls, two rings called as inner and outer-race and a cage. The balls slide between the two rings where the cage holds them in place. Bearings are prone to excessive wear and tear. The faults in the bearings are developed as cracks, pitting, flaking, spalling etc. on the outer-race and inner-race, broken cage and eroded balls. These faults can lead to rotor asymmetry, air-gap fluctuations, eccentricity etc. Sometimes, the faults in the bearing can lead to complete shut-down of the IM. During normal operating conditions, the problems in the bearings start as local fissures in between the surfaces of races and balls. These fissures grow onto the surfaces of the races by gradually breaking the fragments of the material also called spalling or flaking. This results in failure or contamination of the lubrication whose consequence is increased friction between the shaft and the bearing. This process gradually causes severe faults in the bearings. The causes behind bearing faults are as follows:

Causes of Bearing Faults

1. Corrosion and contamination is an important source of gradual wear and tear of bearings. Induction motors are installed in the harsh industrial environment. Foreign material or dirt in the surrounding can fail the lubrication of the bearing. The foreign particles are abrasive in nature which can cause tearing of the bearing material due to continuous exposure. The corrosion in the bearing is caused due to the presence of water, acidic material, fluids around the workplace. They cause chemical reactions that remove of the bearing material and eventually wear of the bearing.
2. In a new bearing, an oil film is present between the balls and the races. During the normal operation, the cage slightly lift off the ball from the races, which prevent the action of oil to lubricate and provide smooth functioning. Excessive heating is caused which breaks the oil and removes the greasing gradually. This reduces the lubrication and friction between bearing parts is increased causing faults in the bearing.
3. During installation, improper and tight forcing of the bearing in the shaft can cause significant misalignment. This also results in brinelling of the bearing that leads to permanent failure.
4. Brinelling is the deformation of the bearing caused due to operation of the motor under excessive loads which break of the elastic limits of the bearing material.
5. False brinelling is a common phenomenon in the failure of bearing, which is caused due to prolonged exposure and vibration in the surrounding. This is the case when the bearing is not in use, and thus vibrations acting on it would not be taken care by the oil film provided.
6. Excessive temperature rise due to a machine's operation is also a reason for bearing failure.
7. Bearings are also failed due to fatigues in the machine.

1.2.2 Stator faults

Stator faults include faults in the stator winding, laminations or the stator core. Stator winding faults are the most common stator faults. There faults arise due to insulation failure which have deteriorating and rapidly propagating tendency. It gradually starts as turn to turn shorts growing in some severe faults. With the shorting of turns, a large short circuit current is flown leading to localized thermal overloading. Eventually, under continuous motor operation, this leads to shorting in the same or adjacent coils, phase to phase or phase/coil to grounding insulation breakdown. Thus, inter-turn faults are the major source of deterioration of the stator winding culminating into wide range of winding faults such as, (1) coil to coil fault, (2) phase to phase fault, and (3) coil to ground fault that may turn severe leading to catastrophic failure of the motor (as presented in Figure 1.7).

Thus, with minor turn-turn short, the situation can gradually worsen to partial or complete burning of the windings and would lead to catastrophic failure of the induction motor. Thus, the

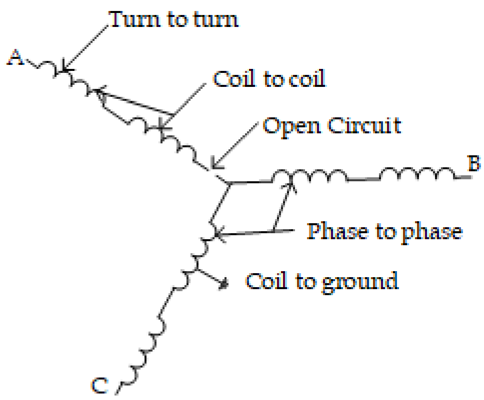

Figure 1.7 : Types of failure modes in a Y-connected stator winding

motor can shut-down within few minutes of these winding faults. Therefore, detection of stator winding inter-turn shorts (SWITS) at an early stage is important and necessary to arrange the maintenance of the motor to prevent it from pre-mature failure. Table 1.2 illustrates the types of faults and immediate consequences in the three-phase stator windings.

Table 1.2 : Types of stator faults with their consequences

Type of stator faults	Consequences
Inter-turn shorts	Motor continues to operate but not long enough
Coil to coil shorts (within same phase)	Motor continues to operate but not long enough
Phase to phase short	Motor fails and protection system will disconnect the supply
Phase to ground short	Motor fails and protection system will disconnect the supply
Single phase out	Motor continues to operate depending on the load

Evidently, the root cause of winding faults is the turn-shorts, soon after which the motor can capture more severe faults resulting in its failure. The insulation failure can be caused by several factors that are briefly discussed below.

Causes of Stator faults

1. The insulation life is affected by an increase in temperature; with every 10-degree rise in temperature, the insulation life is reduced half. Thermal overloading is caused due to variations and unbalancing in the voltage, cycling, improper cooling, and ambient temperature. In general, motors operate satisfactorily within ±10% change in supplied voltage, whereas in the case of voltage unbalance, with every 3.5% voltage unbalance per phase, there is 25% rise in the temperature in the phase carrying the highest current [Bonnett and Soukup, 1992]
2. Frequent start-ups and stops, considerably increase the winding temperature. It is also affected by improper ventilation as heat is generated in the stator and the rotor which if not cooled, may increase the winding temperature quickly.
3. Electrical stresses affect the dielectric i.e. breakages in the insulating material. It is caused due to factors like tracking which involves the formation of high resistance bridge between the copper and the ground. It surpasses the insulating material leading to the ground fault. It generally

occurs when the operating voltage is higher than 600 V.
4. Another phenomenon inducing electrical stress is corona that occurs when the operating voltage is more than 5 kV. The insulating material is subjected to critical voltage level, which leads to gaseous ionization in the insulation.
5. Transient voltage conditions also play a significant role in imposing electrical stresses. These arise due to various faults such as line-line fault, line-ground fault and three-phase faults, opening and closing of circuit breakers, capacitor switching, variable frequency drives.
6. Another category of stresses is mechanical stresses that are developed due to reasons like coil movements, striking by the rotor and causes rendered by other parts of the motor. Due to high current, force is developed in the coils, which causes vibrations leading to movements in both radial and tangential direction. This can result in weakening of the insulation. Striking of the rotor is caused due to bearing faults, rotor misalignment and shaft deflection. Due to these reasons, rotor continuously strikes the stator resulting in the rubbing of stator laminations which can lead to failure of insulation. There are other causes such as loosening of rotor balancing weights, fan, nuts and bolts, which often lead to striking of the rotor.
7. Contamination due to foreign particles (oil, moisture or dirt) also play a major role in reducing the life time of the motor. They can strike the stator, cause bearing failures and also harm insulation in the windings.
8. Cooling is also a concerning factor for deterioration of stator windings. The ineffective cooling system can also aggravate faults.

1.2.3 Rotor faults

Due to excessive stresses, the rotor is subjected to failures in the form of (1) broken bars, (2) cracked end rings, and (3) rotor eccentricity. The most common rotor fault is broken bar rotor fault. Breakages in the bars can be initiated by several reasons including improper installation, overheating, heavy end-rings, rotor-stator rub etc. Because of any reasons, asymmetrical rotor current distribution is present over the rotor whose prolonged existence may result in the development of cracks in the end regions of bar. This causes overheating and thus, it proliferates the gradual breakage of the bar. With the presence of a broken bar, current distribution is significantly changed in the nearby bars, thus making them prone to breakages. They do not cause significant changes in the machine performance in its incipient stages, but, their prolonging effects can cause the abrupt failure of the machine. This type of failure is started by a combination of several stresses acting together with the natural ageing of the motor. The causes behind rotor failures are described below.

Causes of Rotor Faults

1. Due to frequent start/stops, the temperature of the rotor rises which increases the thermal overloading of the rotor.
2. The starting current of five to eight times the rated current, in combination with high impedance cause a high voltage drop across the length of the rotor. This causes flow of current in the laminations which is intermittently interrupted by radial vibrations of the rotor causing the production of sparks. These prolonged rotor sparks are detrimental to rotor's health. A sudden disruptive sparking can cause breakages of rotor bar from the joints of end rings.
3. The slot linkage flux due to the rotor current produces electrodynamic forces which cause the bars to vibrate radially. These causes temporary stresses in the bar which if high, can cause permanent displacement of the bar and eventually an increase risk of the breakages.
4. Unbalanced magnetic pull plays a crucial role in the damage of bars. This can be caused due to bearing faults, eccentricity, load variations, machine alignment. Due to non-uniform magnetic flux, the air-gap is reduced at one end while increased at other, which causes unbalanced magnetic stresses over the rotor. Eventually, the odds of rotor-stator strikes often increases.
5. Mechanical stresses such as loose laminations, broken parts, bent rotor shaft, bearing faults,

misalignment of the rotor shaft, improper rotor/stator geometry can also induce the fault.
6. Some dynamical forces such as transient shaft torques, centrifugal and cyclic stresses also affect the rotor geometry.

1.2.4 Consequences of the incipient faults

The occurrence of faults is an inevitable part of an induction motor. As numerous factors can affect the operation of an induction motor, incipient faults can certainly develop in any of its parts. The prolonged existence of incipient faults in specific part can grow into serious faults; with a high probability of affecting other parts also. These consequences are listed below:

1. Asymmetries in the motor currents, flux linkage and voltages
2. Unbalanced voltages and currents in the air-gap
3. Oscillations in the torque
4. Reduction in average torque
5. Reduced efficiency
6. Increased losses
7. Overheating
8. Excessive vibration and noise

1.3 NEED OF FAULT DIAGNOSTIC TECHNIQUES

These factors give rise to irreversible damage to the motor's health that may lead to the detrimental performance of the motor. This rises unexpected system failure, reduced motor life-time, unscheduled downtimes, production and financial losses. Eventually, in an industrial environment, these causes may affect the working of the whole or a part of the system. This, in turn, brings heavy financial losses due to maintenance/repair, downtime of the sub-systems or sometimes the abrupt shut-down of the system, and in the worst cases, the risk of human lives. The losses are due to low production and wastages of the raw materials. To prevent such detrimental plight of the plant/system, an early fault diagnosis of the incipient faults using the condition monitoring/fault diagnosis of an induction motor becomes an inevitable part of the machine maintenance. This is also called predictive maintenance which helps in dampening the risk of sudden breakouts in the motor; thus allowing the engineer to schedule and prioritize the effective maintenance strategies. This yields timely maintenance of the induction motor without hampering the other processes in the industry. This also helps in planned and organized shut-down of the process plant to repair and maintain the faulty components.

In the last few decades, the monitoring of induction motors has become necessary to avoid unplanned downtime and unexpected financial losses. It has gained the attention of several researchers over a decade for its significant help in operating requirements of the industry. In general, a pool of literature is available for condition monitoring and fault diagnosis for faults occurring in the stator, rotor and the bearings of the motor. Thus, the motivation of this thesis lies in developing algorithms for fault diagnosis, classification and localization based on experimentally collected data of faults in an induction motor using multi-resolution analysis and machine learning tools.

1.4 MOTIVATION

A strong motivation prevails to find an effective fault diagnostic approaches for the induction motor faults. The fault diagnosis techniques (FDTs) proposed should aim for fault detection under various conditions of the motor. These FDTs mainly serve to purpose, 1) fault detection, and 2) fault classification into their broad fault categories then into the sub-classes of faults. Lastly, the location of the fault should also be identified by the algorithms. These techniques should have been verified for simulated faults as well as the faults whose samples can be taken from the industry.

1.5 CONTRIBUTION OF THE THESIS

This thesis revolves around developing fault diagnosis algorithms for three major fault categories of an IM i.e. bearing, stator and rotor faults. Stator currents are affected by both electrical and mechanical faults. Thus, the current based methodology would be helpful for the fault diagnosis due to its non-invasiveness and cost-effective solutions (with the use of cheap sensors). Various algorithms have been proposed for fault detection, its classification into various sub-categories of a fault, followed by locating the fault. These algorithms are based on Stockwell transform and machine learning techniques such as Support Vector Machine (SVM). Stockwell transform (ST) is a multi-resolution analysis technique, phase-corrected version of continuous wavelet transform which uses Gaussian mother wave. The implementation of the ST provides a complex two-dimensional ST matrix producing information in both time and frequency. Support Vector Machine (SVM) has been used to classify the faults into various classes. Cross-validation strategy has been utilized to optimise the relevant parameters of the SVM. Proper kernels are chosen for the analysis. The contribution can be summarized below:

1. For bearing fault diagnosis, the current signals are recorded for the faulty bearings collected from the industry. Total harmonic distortion (THD) based fault index has been identified for fault detection. The fault classification with SVM has been performed using the features extracted from the ST matrix. The optimal features are selected using appropriate methods. Post fault classification, the location has been determined using the fault indexes based on ST matrix.

2. For stator fault diagnosis, inter-turn shorts and ground faults are emulated in the motor. Using statistical features of the ST matrix, fault detection has been achieved. Distinction between turn-faults and ground faults is established, followed by identification of the respective faulty phases using SVM. Two separate models of SVM are trained and tested for both types of stator winding faults.

3. For rotor fault diagnosis, ST matrix has been analysed for detecting the fault. Fault index based on energy of the matrix in the frequency domain is found to be distinguishing for fault detection. Another parameter based on entropy is found to be proportional with respect to the increased the severity of the broken rotor bar faults.

4. The algorithms use feature selection methods to find optimal features for fault diagnosis. This step in the FDTs reduces the computational burden of the final classifier and also reduces the complexity of the algorithm.

In the thesis, three algorithms have been proposed for the detection of bearing, rotor and stator faults respectively. This is an experimental data-based work. The data used is recorded in real-time with faulty components replaced in the motor.

1.6 ORGANIZATION OF THE THESIS

The thesis has been divided into seven chapters. This organisation is done as follows:

1. Chapter-1 includes the introduction to the induction motor with the description of its fundamental components. The faults of the motor and their types have been discussed. The causes and the consequences of the faults have been described for each type of fault. A need for condition monitoring followed by motivation for the thesis has been discussed. Lastly, the contributions of

the thesis has been listed.

2. Chapter-2 discusses the state of the art of the fault diagnosis techniques for bearing, stator and rotor faults in the induction motor. The survey of the literature has been divided on the basis of the domain of the techniques proposed. It is followed by research gaps of state of the art.

3. Chapter-3 details the techniques used in the thesis including Stockwell transform, Support Vector Machine, feature selection methods and Principal Component Analysis.

4. Chapter-4 deals with the bearing fault diagnosis using Stockwell transform and SVM. It begins by introducing the characteristic features of the bearing faults. The methodology has been discussed which follows the fault detection strategy. With the help of Stockwell transform implemented on the current signals, features are extracted under various conditions of the bearing. SVM has been utilised for the fault classification. Subsequent to fault classification, the location of the faulty bearing is identified for all the fault types.

5. Chapter-5 deals with stator fault diagnosis using the current signals recorded for turn-shorts and ground faults emulated in the motor. The features of ST matrix is utilized for the detection of fault. Post fault detection, the fault type has been classified into two categories based on zero-sequence current. The knowledge of the faulty phase is determined using two SVM classifiers for both types of stator winding faults. They classify the samples into three faulty phases.

6. Chapter-6 deals with rotor fault diagnosis using the current signals recorded for broken rotor bars simulated faults. The fault detection is shown along with the parameter, which measures the severity of the fault.

7. Chapter-7 concludes the thesis.

1.7 LIST OF PUBLICATIONS

1. M. Singh and A. G. Shaik, "Stator fault diagnosis of a three-phase induction motor using Stockwell transform and SVM", 1st revision, IEEE Transactions on Instrumentation and Measurement, 2019.

2. M. Singh and A. G. Shaik, "Faulty bearing detection, classification and location in a three-phase induction motor based on Stockwell transform and support vector machine," Measurement (Elsevier), vol. 131, pp. 524–533, 2018.

3. M. Singh and A. G. Shaik, "Broken rotor bar fault diagnosis of three-phase induction motor using discrete wavelet transform,", on Generation, Transmission and Distribution, Proceedings of IEEE PES International Conference and Exposition, 2019.

4. M. Singh and A. G. Shaik, "Location of defective bearing in three-phase induction motor using Stockwell transform and support vector machine.pdf," in International Conference on Power, Energy and Environment, ICEPE, Proceedings of IEEE, 2018.

5. M. Singh and A. G. Shaik, "Bearing fault diagnosis of a three-phase induction motor using Stockwell transform," in India Conference (INDICON), 13th IEEE Annual, 2016, pp. 1–6.

6. M. Singh and A. G. Shaik, "Application of Stockwell transform in bearing fault diagnosis of induction motor," in Power India International Conference (PIICON), 7th IEEE, 2016, pp. 1–6.