VSB TECHNICAL UNIVERSITY OF OSTRAVA | FACULTY OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

Offline Diagnostic of Rotor of Asynchronous Motor

Offline diagnostika rotoru asynchronního motoru

S. M. Shar-Atul Hasan, B.Sc.

Diploma Thesis

Supervisor: **doc. Ing. Petr Kačor, Ph.D.**

Ostrava, 2023

Ref. no.VSB/22/078390

vsboee22025E2E

Diploma Thesis Assignment

Student: **S. M. Shar-Atul Hasan, BSc**

Study Programme: N0713A060004 Electrical Power Engineering

Title: Offline Diagnostic of Rotor of Asynchronous Motor

Offline diagnostika rotoru asynchronního motoru

The thesis language: English

Description:
1. Introduction to offline diagnostic.
2. The fundamental methods and processes used in rotors diagnostic of asynchronous motor.
3.1 Electromagnetic FEM analysis of the rotor with simulation of its typical defects.
3.2 Diagnostic measurement of the rotor in laboratory conditions on a test device.
3.3 Comparison of simulated and measured values by FFT analysis.
4. Final evaluation of the performed work.

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Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

Supervisor: **doc. Ing. Petr Kačor, Ph.D.**

Date of issue: 01.09.2022

Date of submission: 30.04.2023

Study programme guarantor: prof. Ing. Stanislav Rusek, CSc.

In IS EDISON assigned: 02.11.2022 15:23:12

Abstract

Asynchronous machines are widely used in various industrial applications, and their reliable operation is essential to maintain the production process. Rotor faults are one of the most common types of faults in asynchronous machines and can lead to a significant decrease in the machine's efficiency and lifespan. Offline diagnostic methods have been developed to detect rotor faults in asynchronous machines, including vibration analysis, current signature analysis, and motor current signature analysis. This research paper presents an overview of offline diagnostic methods for detecting rotor faults in asynchronous machines, their principles, advantages, and limitations. The paper also includes case studies of rotor fault diagnosis in asynchronous machines using Finite Element Method (FEM) and FFT analysis for Maxwell 2D electromagnetic FEM model.

Keywords: Asynchronous Motor, Offline Diagnostic, FEM, MCSA, Broken Rotor Bar, 2D Electromagnetic Model, Stray Flux, FFT.

Abstrakt

Asynchronní stroje jsou široce používány v různých průmyslových aplikacích a jejich spolehlivý provoz je nezbytný pro zachování výrobního procesu. Poruchy rotoru jsou jedním z nejčastějších typů poruch asynchronních strojů a mohou vést k výraznému snížení účinnosti a životnosti stroje. Pro detekci poruch rotoru asynchronních strojů byly vyvinuty offline diagnostické metody, včetně analýzy vibrací, analýzy proudové signatury a analýzy proudové signatury motoru. Tento výzkumný článek uvádí přehled offline diagnostických metod pro detekci poruch rotoru asynchronních strojů, jejich principy, výhody a omezení. Článek rovněž obsahuje případové studie diagnostiky poruch rotoru asynchronních strojů pomocí metody konečných prvků (MKP) a analýzy FFT pro Maxwellův 2D elektromagnetický model MKP.

Acknowledgments

My sincere gratitude to my thesis supervisor **doc. Ing. Petr Kačor, Ph.D.**, for his invaluable guidance, encouragement, and support throughout my research. His vast knowledge, expertise, and insightful comments have been instrumental in shaping the direction of my work and providing me with invaluable guidance on the technical aspects of my thesis.

Also, I also thank **Ing. Jan Fulneček, Ph.D.** and **doc. Ing. Petr Krejčí, Ph.D.**, for his unwavering support and encouragement throughout my research. Their invaluable insights, technical support, and unwavering encouragement have allowed me to complete this investigation.

My sincere thanks also go to my parents for their unconditional love, support, and encouragement throughout my studies. Their support has been a constant source of inspiration for me and has allowed me to pursue my academic goals with confidence and determination.

Finally, I express my gratitude to the Department of Electrical Power Engineering **at the VSB-Technical University of Ostrava**, for providing a stimulating academic environment to pursue my studies. Collaborating with such esteemed academics and researchers has been a privilege and an honor I will cherish for the rest of my life.

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List of used Symbols and Abbreviations

Symbol	Units	Meaning of Symbol
$n_{sync.}$	rpm	Synchronous Speed
f	Hz	Frequency
S	%	Slip
P	-	No. of Pole in Stator
V	ms^{-1}	Velocity of Magnetic Field
B	T	Magnetic Field
L	m	Length of the Conductor
n	rpm	Mechanical Shaft Speed
μ_0	H/m	Permeability of Vacuum
b	m	Slot Width
Δf	Hz	Shift Frequency
dB	-	Sideband
T	sec	Time
$a_0, a_n\ b_n$	-	Fourier Coefficient
f_{BAR}		Fundamental Frequency of Broken Rotor Bar
IM	-	Induction Motor
ASM	-	Asynchronous Machine
FEM	-	Finite Element Method
RMF	-	Radio Magnetic Field Coil
MCSA	-	Motor Current Signature Analysis
	-	
2D	-	Two Dimension
BRB	-	Broken Rotor BAR
FFT	-	Fast Fourier Transform

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1 Introduction

Asynchronous machines are widely used in various industrial applications, such as pumps, compressors, and fans, because of their simple construction, high efficiency, and minimal maintenance cost. However, like any other machine, asynchronous machines are subject to faults that can lead to downtime, production losses, and maintenance costs. Rotor faults are one of the most common types of faults in asynchronous machines and can lead to a significant decrease in the machine's efficiency and lifespan.

Diagnostic faults in asynchronous machine rotors are typically performed using online monitoring systems. These systems continuously monitor machine parameters, such as current, voltage, and temperature, and analyze them to detect faults. However, online monitoring systems have limitations, such as high cost, complexity, and the need for uninterrupted machine operation, which may not be feasible in some applications. In such cases, offline diagnostic methods can diagnose rotor faults. Off-line diagnostic methods involve performing tests on the machine when it is not operating, making it a more cost-effective and practical solution for some applications.

This research paper presents an overview of the offline diagnostic methods for detecting rotor faults in asynchronous machines, their principles, advantages, and limitations. The paper also includes case studies of rotor fault diagnosis in asynchronous machines using offline diagnostic methods using the Electromagnetic Finite Element Method (FEM) analysis.

1.1 Asynchronous Machine

Asynchronous motors can be considered among the most reliable electrical machines, and they perform their function for many years with reduced maintenance and adapt to different performances according to the requirements of production and service applications [1].

An asynchronous machine is an AC electric motor that operates without a synchronized speed between the stator (stationary) and rotor (rotating) parts. As such, it is also known as an induction motor (IM).

Induction motors were invented by Nikola Tesla in 1888. Their rotating parts do not require an electrical connection because electromagnetic induction will transfer energy from the stationary parts to the rotating counterpart. The stationary winding, named a stator, can produce a rotating magnetic field, which induces an alternating electromotive force and current in the rotor. The induced rotor current and the rotating field of the stationary winding interact and produce motor torque. The characteristic of the induction motor torque speed is related to the resistance and reactance of the rotor. Therefore, it is possible to achieve different torque-speed characteristics with different ratios of rotor resistance to rotor reactance in rotor circuits [2].

In an asynchronous machine, the rotating magnetic field generated in the stator induces a current in the rotor, which creates a magnetic field that interacts with the stator's magnetic field to produce a torque that causes the rotor to rotate. The speed of the rotor is lower than the synchronous speed.

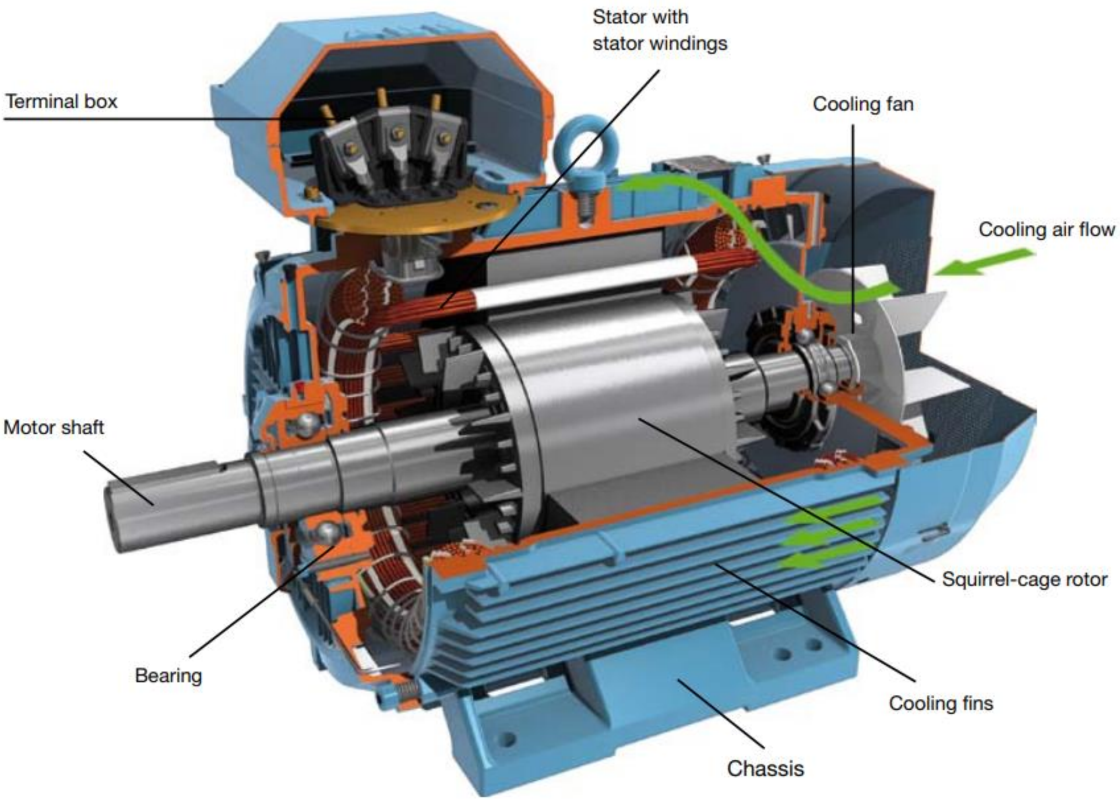


Figure 1. 1: Asynchronous Machine [1]

1.2 Construction of a Three-Phase Induction Motor

Before understanding the faults in the machine, it is necessary to understand the construction of an asynchronous machine. The basic structure of an IM consists of a stator, which is the stationary part of the machine, and a rotor, which is the rotating part of the machine.

1.2.1 Stator

The stator, shown in Figure 1.4, comprises a laminated core that carries a three-phase winding, which produces a rotating magnetic field. It comprises a cylindrical iron core with evenly spaced slots on its inner periphery. Insulated copper wire coils are wound into these slots to form the stator windings. The number of slots in the stator corresponds to the number of poles in the motor [1].

The stator windings of a machine with P poles are positioned at an angular distance of (2/P) (2π/3) radians concerning each other. Additionally, each phase belt is uniformly distributed across equal slots. This statement encapsulates the relevant technical specifications of the machine clearly and concisely suited to academic writing conventions. The terminals of the three-phase stator windings can be configured in a wye (Y) topology [1].

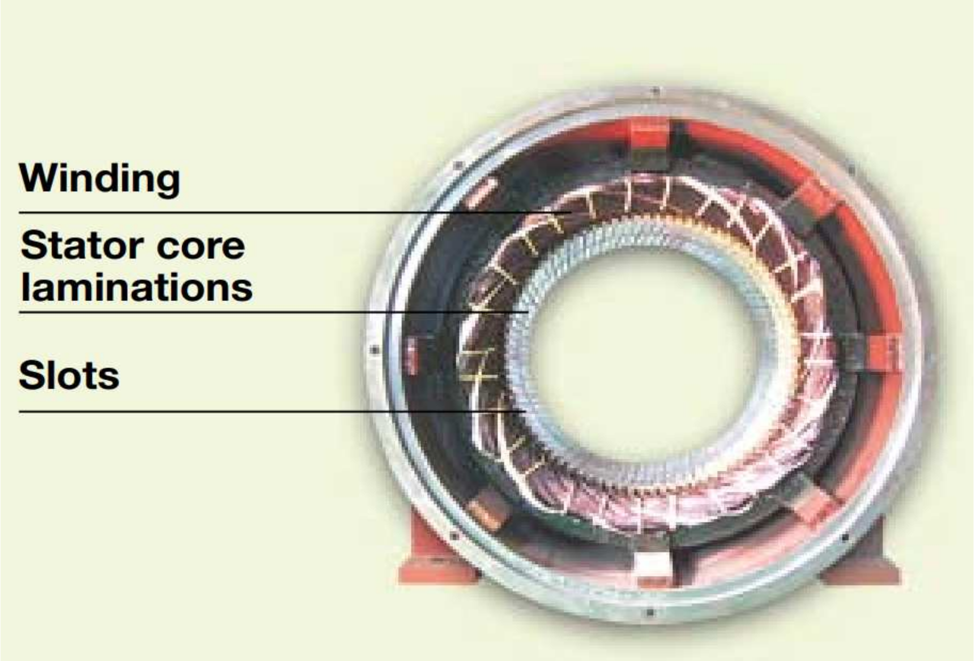


Figure 1. 2: Stator of a Three-phase Asynchronous Motor [1]

1.2.2 Rotor

The rotor shown in figure 1.5 comprises a laminated core with conductors that are short-circuited at the ends, forming a squirrel cage. The rotor rotates in the magnetic field created by the stator, and the interaction between the rotating magnetic field and the rotor conductors produces torque, causing the rotor to rotate [1].

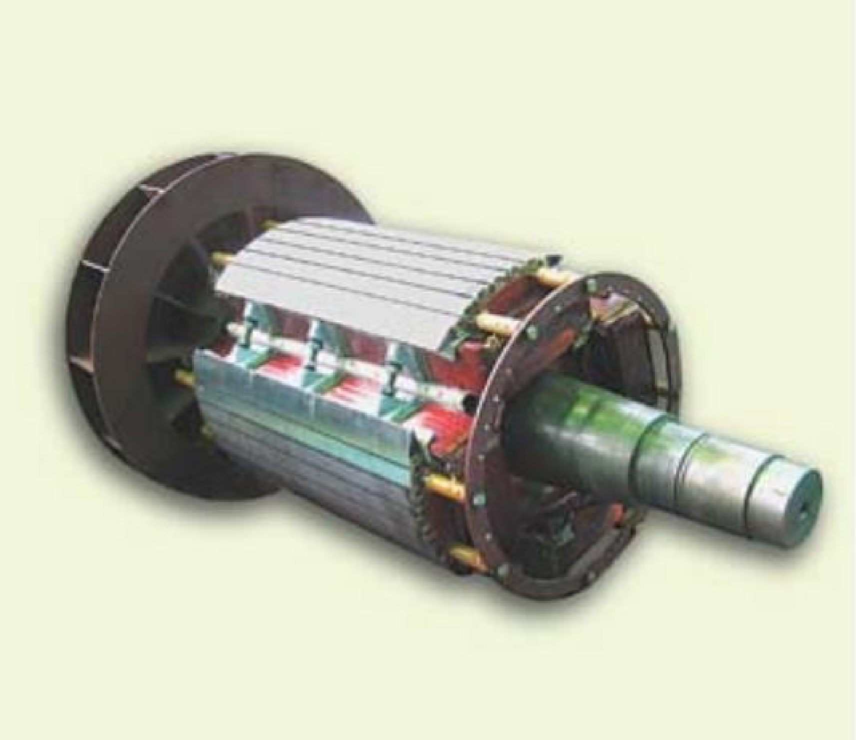


Figure 1. 3: Rotor of a Three-phase Asynchronous Motor [1]

1.2.3 Bearings

Bearings are constructed from combinations of ball bearings and flanges. The process of inserting ball bearings into the motor shaft while the latter is still hot is carried out to guide the shaft's rotation. The connection between the stator body and the flanges, manufactured from cast iron alloys, involves using bolts or rods [3].

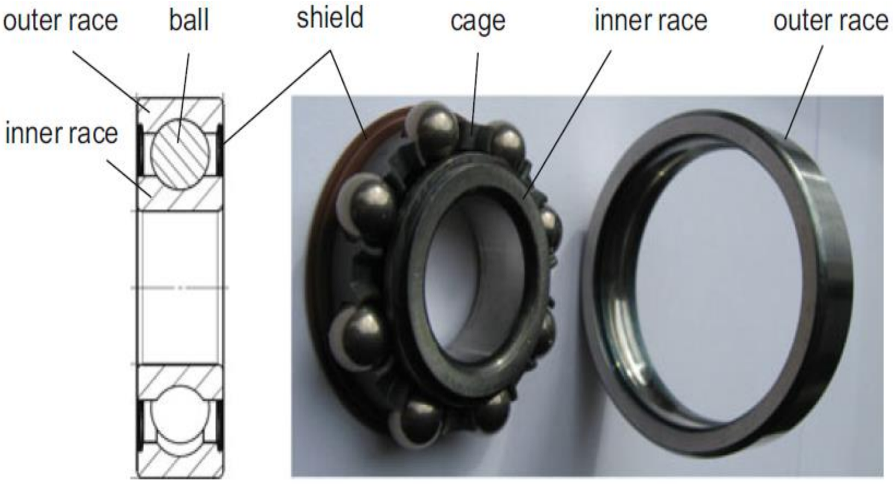


Figure 1. 4: Bearing [5]

In summary, the construction of an asynchronous machine consists of a stationary stator with a cylindrical iron core wound with copper wire to create the stator windings and a rotating rotor with copper or aluminum bars placed in slots and connected by shorted rings, all separated by a small air gap.

1.3 Types of Asynchronous Machine

Asynchronous machines are classified into two types as follows.

- *Squirrel-cage induction motor, and*
- *Wound rotor or slip ring induction motor.*

1.3.1 Squirrel-Cage Induction Motor

Squirrel cage induction machines are the most common asynchronous machine used in industry. They are called squirrel-cage induction machines because of their rotor design, which looks like a squirrel cage.

The rotor comprises conductive bars or rods that are short-circuited by two end rings at both ends, forming a cage-like structure. Rotor bars are usually made of aluminum, copper, or brass. The stator windings produce a rotating magnetic field, which induces a current in the rotor bars. The interaction between the rotating magnetic field and the rotor current produces torque, causing the rotor to rotate.

Squirrel cage induction machines, such as pumps, fans, compressors, and conveyors, are widely used in low- and medium-power applications. They have simple construction, low maintenance cost, and high reliability.

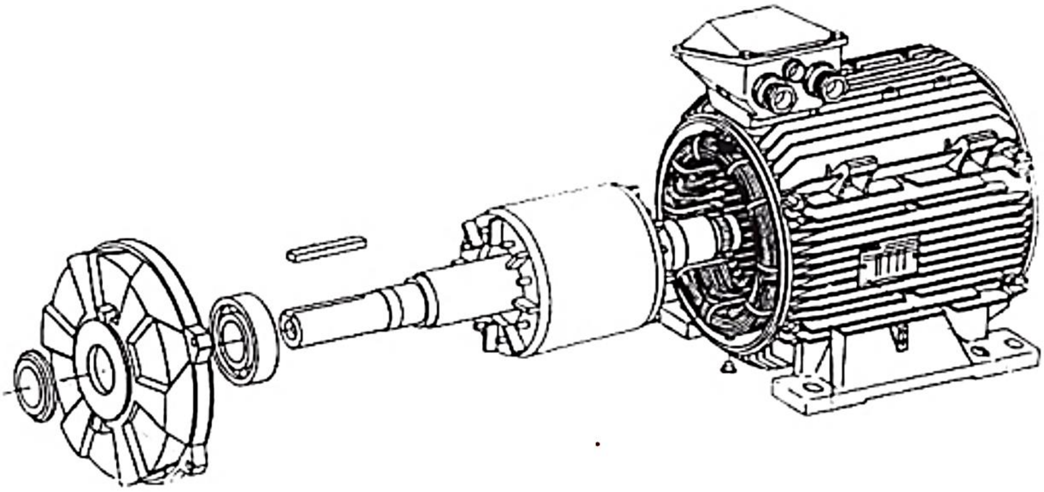


Figure 1. 5: Leroy-Somer Induction Squirrel Cage Motor [3]

1.3.2 Wound Rotor or Slip Ring Induction Machines

Wound rotor induction machines have a similar construction to squirrel cage induction machines, but their rotors are wound with insulated wire instead of being made up of conductive bars. The rotor windings are connected to slip rings, which allow external resistors or capacitors to be connected to the rotor circuit. Slip rings also allow the rotor windings to be connected to an external power supply, making it possible to vary the rotor voltage and frequency independently of the stator voltage and frequency [4].

Wound rotor induction machines, such as large pumps, compressors, and cranes, are used in high-power applications. They provide better starting torque, speed control, and efficiency than squirrel-cage induction machines but are more complex and require more maintenance.

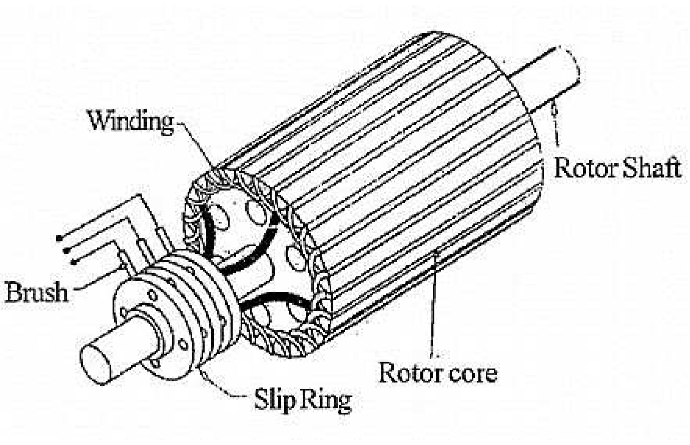


Figure 1. 6: Wound Rotor Induction Motor [4]

1.3.3 Difference between the Squirrel Cage and the Wound Rotor or Slip Ring Induction Motor

The primary difference between a squirrel cage induction motor and a wound rotor induction motor lies in the rotor construction.

Squirrel cage induction motors have rotor bars that are short-circuited at the end rings, preventing the connection of external resistance. On the other hand, slip-ring induction motors connect external resistance in the rotor circuit through a star connection.

Due to the simplicity of construction, high overload capability, high efficiency, low maintenance expense, and low cost, the squirrel cage motor is widely used in industry [4].

1.4 Working Principle of a Three-Phase Asynchronous Machine

Asynchronous machines work on the principle of electromagnetic induction. A rotating magnetic field is produced when a three-phase AC voltage is applied to the stator winding. The rotating magnetic field induces an electromotive force (EMF) in the rotor winding by Faraday's law, which causes a current to flow in the rotor conductors. The interaction between the rotor current and the rotating magnetic field produces torque, which causes the rotor to rotate.

Furthermore, when the stator is energized with an AC voltage, it produces a rotating magnetic field. This rotating magnetic field induces a current in the rotor bars, creating a magnetic field. The interaction between the magnetic field of the stator and the rotor's magnetic field produces torque, causing the rotor to rotate. [1]

The speed of the rotating magnetic field is called the synchronous speed and is given by the equation,

$$n_{sync.} = \frac{120f}{P} \tag{1.1}$$

where $n_{sync.}$ is the synchronous speed (rpm), f is the frequency (Hz), and P is the number of poles on the stator [6].

Faraday's law elucidates that an electromotive force (emf) is engendered in a closed circuit in direct proportion to the rate of variation of magnetic flux encountered by the circuit. Consequently, the copper bar undergoes induction of EMF, leading to the generation of current in the rotor. It expresses that the following equation,

$$emf = (v \times B) \cdot l \tag{1.2}$$

where v is the velocity of the bar relative to the magnetic field (ms^{-1}), B is magnetic flux density (T), and l is the length of the conductor (m) in the magnetic field [6].

The direction of the rotor may be ascertained through the application of Lenz's law, which posits that "The direction of the induced current will be opposite to that of the motion which gives rise to it."

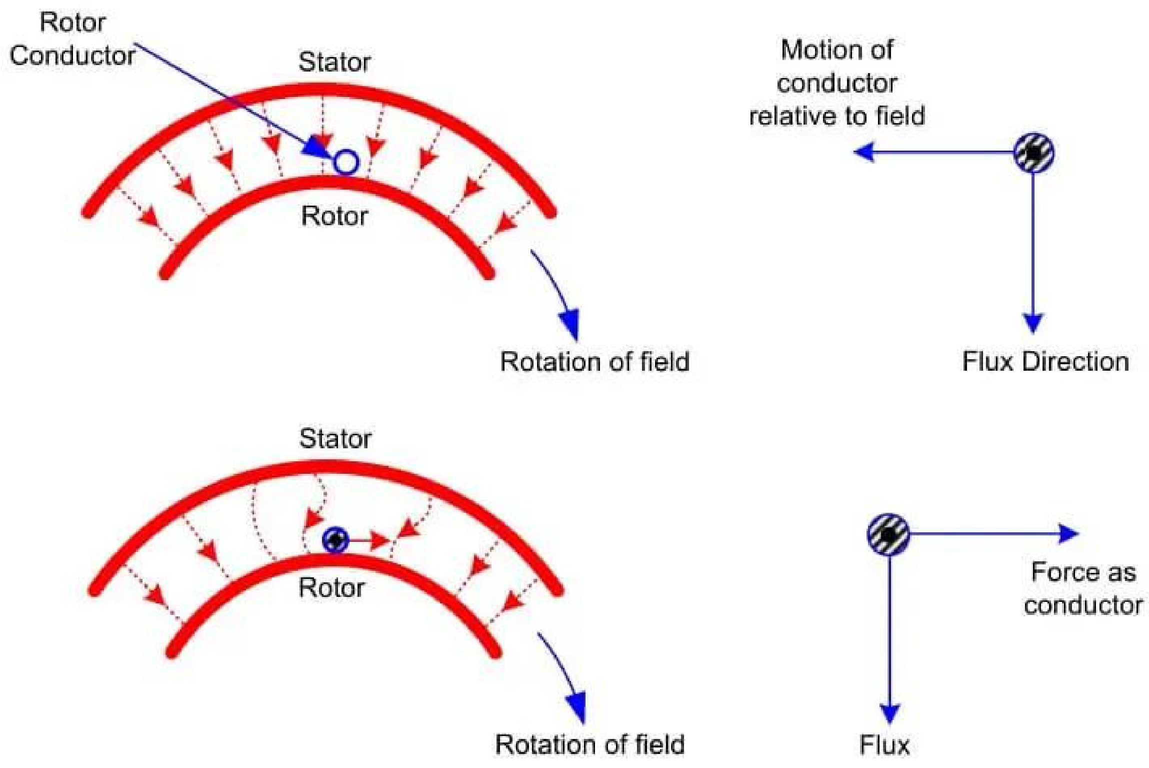


Figure 1. 7: Working Principle of an Asynchronous Machine [7]

The current generation in a static rotor conductor is attributed to the relative velocity between the rotating flux and the conductor. As a result, the rotor will rotate in the same direction to mitigate this causal factor. The motion of the rotor in the induction motor is caused by the relative velocity occurring within the system, which results in the rotor's rotation [7].

The speed of the rotor is slightly lower than the stator's rotating magnetic field, creating a slip. If the rotor rotates at synchronous speed, there would be no induction, and the motor would have zero torque.

The lag of the rotor behind the stator magnetic field is defined by the slip, s by the following equation,

$$s = \frac{n_{sync} - n}{n_{sync}} \times 100\% \tag{1.3}$$

where $n_{sync.}$ Is the synchronous speed of the magnetic field, n mechanical shaft speed of the motor (rpm) [6].

1.5 Failures Overview on Induction Motor

Despite reports of robustness, the induction machine occasionally exhibits various faults. Various defects have been identified in disparate components of the machinery, beginning with the stator phase linkage, and culminating in the mechanical interconnection between the rotating shaft and the load. The occurrences of failures can be anticipated or unanticipated and may stem from mechanical, electrical, or magnetic factors that originate from distinct origins. According to a statistical investigation conducted by [8], discernible patterns of failure frequency have been identified concerning the squirrel-cage induction machines utilized in the petrochemical sector. A visual representation of these patterns is presented in Figure 1.8, where the relative proportions of the types of failure that may affect these heavy-duty machines are illustrated. The distribution presented demonstrates that malfunctions in high-capacity machinery arise predominantly from the bearings and the stator coil, which can be attributed to this apparatus's more significant mechanical restraints [3].

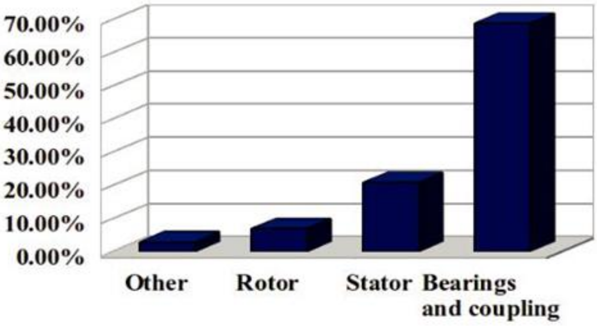


Figure 1. 8: Fault percentages in 2008 [3]

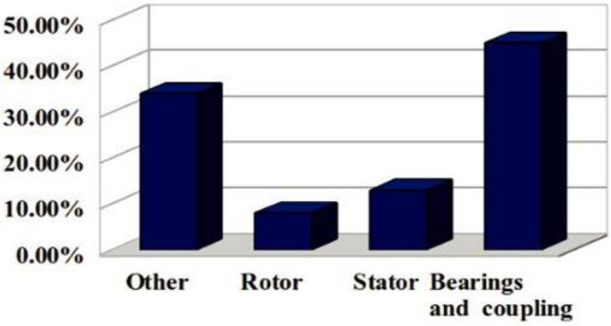


Figure 1. 9: Fault percentages in 1995 [3]

According to this research, faults in high-powered machines mainly stem from the bearings and the stator coil, which is due to more significant mechanical constraints in the case of this machine.

Asynchronous motors have become the superior choice of electric motors in various industrial applications. Asynchronous motors have gained popularity for various applications, mainly attributable to their versatility in function, affordability in procurement and maintenance, and robust construction that minimizes maintenance demands. In a manner analogous to other rotating machinery types, asynchronous motors are not impervious to component malfunctions, despite being considered highly dependable.

However, these faults can be categorized into mechanical, electrical, and combined mechanical and electrical faults.

Mechanical failures include rotor imbalance, misalignment, bearing wear, and shaft breakage. These faults can increase vibration and noise and reduce machine efficiency.

Electrical faults include rotor bars or end rings, stator winding, and insulation failure. These faults can result in increased current, temperature, and reduced machine performance.

Combined mechanical and electrical faults can occur when a mechanical fault leads to an electrical fault or vice versa. For example, a rotor imbalance can cause rotor bar failures, while electrical failures can cause increased mechanical stress and wear on the rotor. Moreover, defects can be categorized based on the corresponding component of the apparatus in question in the following manner.

As an approximate indicator of component failure rate, it states that components with the most frequent occurrence of failures in an asynchronous motor are bearings (40%), followed by stator windings (38%), other components - terminals, plates, cooling, etc. (12%), and rotor (10 %). The percentage distribution is not always specific, as it may vary for machines of different sizes, lifetimes, power, weight, operations, etc. [9].

Faults in the machine are always manifested by the generation of undesirable harmonics and intermediate harmonics, including harmonics with both higher and lower levels than the primary harmonics, which result in torque pulsations, reduction in the machine's achievable torque, increase in power losses, or excessive heating.

A discernible trend emerges when conducting a comparative analysis of the present research findings with those collected in previous studies by [10], as presented in Figure 1.9, for machines of similar type such as 100 kW to 1 MW. Specifically, it is evident that in recent times, the distribution of fault percentages has been subject to modification, possibly due to variations in the manufacturing conditions involved in the construction of the motors. The incidence of faults in the stator and rotor has declined noticeably, while the predominant cause of malfunction at present stems from the bearings. The advent of power electronics has facilitated innovative yet feasible, means of implementing novel means of regulating electrical apparatus. In the case of machines governed by power converters, the bearings are subjected to voltages that comprise elevated-order harmonics. The alternative has been established as the normative approach for managing electrical systems. This variety of power supply expedites the deterioration of the insulating material within the stator winding. One possible resolution is the development of an improved material insulator. The statistical data presented in this context cannot be considered universally applicable, as it is imperative to acknowledge that the prevailing operating parameters of the machine markedly influence the observed flaws. Furthermore, it is pertinent to note that the possible causes underlying these discrepancies may be diverse and multifactorial [11]. For example, it is prudent to enumerate the various etiological factors presently as follows [3]-

- *Mechanical failures resulting from deficient manufacturing processes, machine vibrations, imbalanced electromagnetic forces, centrifugal forces, and load fluctuations represent significant concerns within the field.*
- *The electrical system may encounter various hazards, including insulation damage, partial discharge, and sparks.*
- *In the scope of thermal considerations, the phenomenon of copper losses and inadequate provision of both general and localized cooling are pertinent issues.*
- *The environmental factors under consideration include air humidity and dust particles.*

The summarized causes of stator and rotor faults are presented in Table 1.1- [12]

	Faults	Causes
Stator	Frame vibration	Magnetic imbalance, coil vibration, power supply imbalance, overload, bad installation, and contact with the rotor are caused by vibration faults.
	Fault between coils and the stator frame	It occurs due to the coil being pressured by the frame, thermal cycle, poor insulation, angular points in the slots, and shock.
	Insulation fault	Insulation damage during installation, frequent starting, and extreme temperature conditions are caused by insulation failure in the IM stator.
	Inter turn to short-circuit	It can occur due to excessive temperature, high humidity, vibration, and over-voltage supplied in the motor.
	Interphase Short-circuits	It is caused by insulation failure, high temperature, imbalanced supply, and coil slacking.
	Displacement of the Conductor	Shock, frequent starting, and winding vibration are responsible for this fault.
	Failure of the connection	Due to conductor pressure and excessive vibration, it can damage the stator connection.
Rotor	Bearing fault	Bearing faults can occur due to bad installation, magnetic imbalance, overload, loss of lubricant, high temperature, lack of cleanliness, and unbalanced load.
	Bar breaks	Magnetic imbalance, overload, loss of lubricant, high temperature, lack of cleanliness, unbalanced load, and thermal fatigue can break the bar.
	Failure of the magnetic circuit	It can happen due to a manufacturing fault, thermal fatigue, or overload.
	Misalignment	Due to poor installation, bearing failure, overload, and magnetic imbalance.
	Bearing lubrication fault	For excessive temperature or poor-quality lubricant.
	Mechanical imbalance	The short-circuit ring movement and alignment problem cause it.

Table 1. 1: Faults in the Induction Machine and their Causes [3]

1.6 Objectives

The thesis combines simulation and laboratory measurement of rotor faults detection in induction machines. The measured data and 2D FEM electromagnetic model analysis is a technique to detect the broken rotor bar faults with corresponding frequencies by FFT analysis. The RMF coil is used for detecting magnetic stray flux.

By establishing a comprehensive fault detection approach, the objective is to facilitate timely maintenance actions, prevent catastrophic failures, optimize machine performance, and extend the overall lifespan of asynchronous machines. The main objectives are-

- *To familiarize the reliability in offline diagnostics for detecting Asynchronous Machines.*
- *Use Maxwell 2D FEM electromagnetic model for the process of rotor faults detection.*
- *Analysis and experimental evaluation by Frequency analysis by the FFT.*
- *Compare the results variation in simulation and Practical Measurement.*

1.7 Organization of the Thesis

The current research pertains to exploring offline diagnostic approaches for detecting rotor faults in asynchronous machines through the utilization of the Finite Element Method (FEM) and Fast Fourier Transform (FFT) analysis implemented with the ANSYS Maxwell software, along with the compared results from practical measurements in the laboratory. This study comprehensively elucidates fundamental concepts and necessary depictions in five chapters.

Fundamentals of asynchronous machines and overviews of their faults are briefly discussed in the first chapter.

In the second chapter, the theories of technical diagnostics, methods to use, and offline and online diagnostics were described to understand how faults were detected in an induction motor.

The third chapter deals with the fundamental methods and processes used in rotor faults diagnostic of asynchronous motors.

Chapter Four presents an electromechanical FEM model analysis of the rotor, along with a simulation of its typical defects with FFT analysis.

The fifth chapter, the diagnostic measurement of the rotor in a laboratory and analysis of faults conditions with FFT spectrums with evaluations of finding about the simulation and practical measurements.

2 Diagnostic

The fault diagnosis process is based on the occurrence of a fault within a device, and its objective relates to identifying that fault through implementing a relevant diagnostic methodology [13]. As elucidated subsequently, it assumes a particular function in the realm of technology, particularly in the context of problem diagnosis and resolution.

In the field of electrical machines, fault occurrence inherently produces an asymmetry in the magnetic field. The asymmetry will propagate to distinct electromagnetic parameters such as currents, voltages, magnetic flux, mechanical and electric power, torque, and speed. The diagnostics engineer is required to monitor and analyze the variables to identify any potential deviations from the typical characteristics of the machine that are consistent with optimal functioning. According to Figure 2.1, the diagnostic method has shown the most critical characteristics [13].

Therefore, it is essential to emphasize and prioritize this matter accordingly.

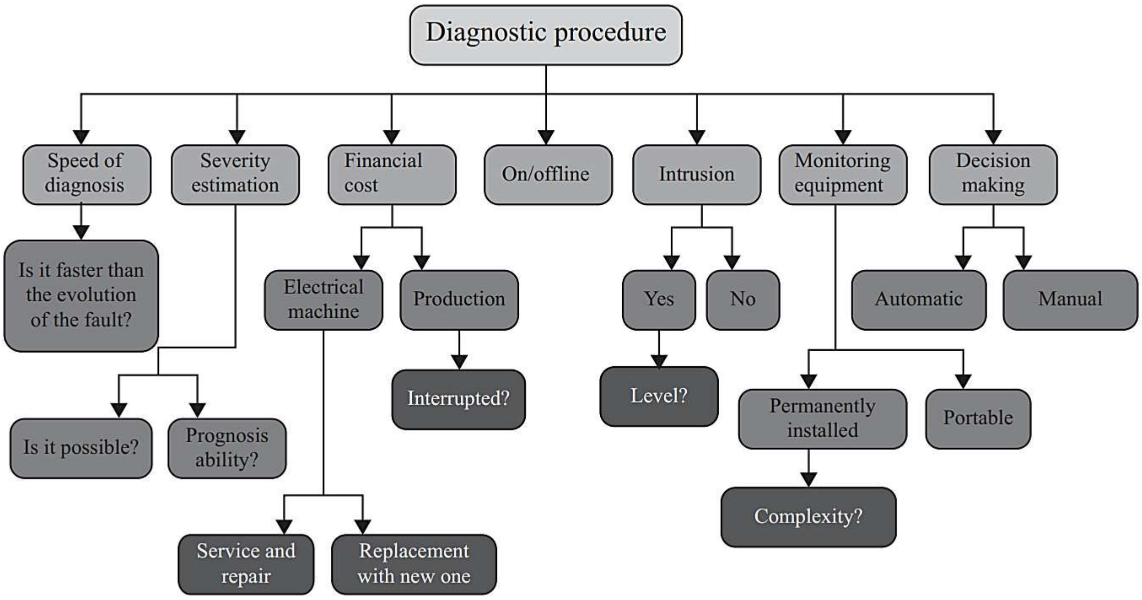


Figure 2. 1: Diagnostic procedure characteristics [13]

2.1 Technical Diagnostics and It's Meaning

Technical diagnostics is a systematic field of study dedicated to collecting relevant data on the technical condition of a predetermined object through the utilization of diverse methodologies, techniques, and resources. Its primary objective is to identify and isolate any faults present and ascertain the extent of their possible impact. Diagnostics plays a crucial role in all processes pertaining to device manufacturing, training, and operation, thereby occupying a significant position. The methodical examination of the situation of objects constitutes a cutting-edge topic due to the ever-increasing financial and reliability requisites. The timely identification of emerging faults and appropriate intervention measures can effectively preserve significant economic resources by mitigating exorbitant repairs and circumventing the cessation of mechanical devices. Therefore, it is advantageous to identify machines that exhibit an elevated purchase cost and significant relevance within the context of the application system.

Regarding the time aspect, essential terms in the diagnostic test can describe the current developmental state of the system over a specific period. The prognosis evaluates the current functionality of the identified object and serves as an assessment of its operational status considering the current circumstances.

The concept of a forecast entails predicting the future enhancement of the technological state of an entity and associated determinations regarding the likelihood of potential failures based on the object's past operational history. The genesis of this study involves an assessment of potential factors contributing to the disease and an exploration of the ongoing and detrimental deterioration of the device. The categorization of technical diagnostics can be delineated based on various criteria in the subsequent manners as follows [14]

- *Direct and indirect*
- *Partial and total*
- *Interoperation, output, and operational*
- *Comprehensive and in-depth*
- *Subjective and objective*
- *Faults and malfunctions and functional*

Material engineering is esteemed as a fundamental scientific discipline about diagnostic processes when considering the creation and development of electrical equipment. This is aimed at assuring the fundamental material components vital for the given application. Consequently, selecting and modifying materials or their arrangements are deemed suitable to fulfill the task's demands and correspondingly align with the specified objectives. The initial stage of electrical engineering diagnostic procedures can be attributed to the appropriate selection and strict adherence to material constraints. Through diligent investigation at the production stage, identifying and excluding non-conforming product components or their constituent parts is attainable, thereby averting the propagation of said components to subsequent production phases. This measure effectively curbs manufacturing anomalies in the ultimate apparatus, facilitating substantial financial benefits and other pertinent advantages.

Similarly, the outcomes of the inspection conducted at the manufacturing facility can identify the diagnosis of the final product. This is achieved by detecting segments presenting a likelihood of failure and minimizing them through appropriate inspection methodologies, thereby circumventing undesirable warranty repairs.

The field of diagnostics encompasses the exploration of deficiencies that emerge during the functioning of a device and their underlying causal factors. Operational failures typically exhibit a close association with structural imperfections. The consistent occurrence of failures indicates that alternative, more compatible components have been employed, thus imparting critical intelligence to produce the device. Using this approach, one may also ascertain deficiencies within their production procedures should they materialize due to a non-functioning production process. One potential factor contributing to the manifestation of malfunctions could be attributed to an inadequate work environment. Specifically, recurrent breaches of established working condition parameters may signal excessive workload. The action will yield the essential factor for site eviction load.

At present, there exist two primary facets of electrical apparatus. The initial facet to consider is the acquisition cost of the machinery, with a premium placed on expeditious recuperation of investment. The second aspect pertains to the essential need for equipment preparedness, a crucial component in dependability and maintainability. The notion of sustainability pertains to the capacity of a device to be reinstated to its initial factory state through maintenance. Successful execution of electrical diagnostics requires careful adherence to the conditions and assumptions delineated above [14].

2.2 Diagnostic Structure of the Object

One significant aspect of the diagnosis process pertains to the presence of the diagnostic object and the technical methodologies and approaches used to execute object diagnostics effectively. The present statement posits that the diagnosable entity is a comprehensive construct that amalgamates various functional systems and subsystems, each characterized by a distinct configuration. Such a construct assumes a pivotal role in diagnostic investigations. Throughout their lifespan, these entities are subject to various external stimulation, or inputs, to which they generate corresponding signals, or outputs, as responses. In essence, the diagnostics process can be characterized as examining both the inputs and outputs. A constructive perspective suggests that diagnostic objects can be classified into two groups [15], such that-

- *Accessible internal structure and*
- *Inaccessible internal structure.*

2.2.1 Accessible Internal Structure

The object is deemed to have an accessible internal structure when endowed with effortlessly retrievable structures. Through the thorough analysis and scrutiny of incoming and outgoing data, one can delve deeper into the inner machinations of a given entity. This approach consequently presents an occasion for assessing and identifying precise anomalies. As mentioned earlier, the capacity significantly augments the diagnostic and analytical procedures.

2.2.2 Inaccessible Internal Structure

The internal structure of an object that is inaccessible and whose structural details cannot be studied is not deemed pertinent to the internal processes concerned with it. Given that the equipment's operation relies solely on the input and output variables, it is essential to ensure that they remain within prescribed limits to ensure optimal performance.

2.3 Methodology of Diagnostic Tools

Diagnostic tools refer to various procedures and devices utilized to examine and subsequently assess the condition of an entity. Consequently, they encompass specific diagnostic techniques, algorithms, and instrumentation that facilitate pragmatic functionalities in executing these methods. At times, an individual may be regarded as a diagnostic instrument that regulates the functionality of a particular apparatus. Various states of the diagnosed device can be classified based on an analysis of its service life. When the operational condition of the system is favorable, it exhibits indications of accurate performance, and all parameters remain within the stipulated thresholds. The opposite phenomenon refers to a malfunction that impedes the successful execution of the system's designated function. Such an occurrence is typical if a function is executed with constrained proficiency. The diagnosed operating conditions significantly influence the optimal performance and durability of the operating object, thereby ensuring its maintenance in a reliable state. When adhering to all operational regulations and policies about equipment maintenance, it is crucial to consider common operating conditions. In dry conditions, the etiology of failure is primarily rooted in internal factors rather than external circumstances. The underlying cause of such malfunction is typically attributed to sub-optimal design or deficient construction of the subject entity. When an operation is conducted under abnormal conditions, it indicates a failure to satisfy the necessary prerequisites for primary operating conditions. Therefore, the root cause of the ensuing disorder can typically be traced back to external factors, such as improper operation or unauthorized access to the device. This observation highlights the importance of adhering to prescribed operating conditions to ensure system stability and avoid undesirable outcomes. The gradual degradation of the technical state typically manifests itself, and the malfunctions may assume divergent forms. Concerning the constituent materials, there is a possibility of failures in distinct components attributable to causes such as corrosion, adhesion, abrasive forces, fatigue, vibration-induced wear, and deformations like cracks or other mechanical faults. The occurrence of faults can be categorized into two parts as follows [15]-

- *Based on an analysis of the probability and magnitude of the faults:*
    - *Full and fractional*
    - *Sudden and continuous*
    - *Lasting and transitory*
    - *Arbitrary and non-random*
    - *Subordinate and autonomous*
- *Based on the methods utilized and the source of fault location:*
    - *Structural defects*
    - *Technological failures*
    - *Operational failures*

Diagnostic procedures offer insights into the existing technical condition of a valuable entity. If the output variable lacks quantifiability, it must first convert into a form that conforms to accepted standards. This may be achieved by generating a corresponding set of signals that mirror the corresponding states of objects. The mechanism facilitating the transformation is referred to as a diagnostic system. A crucial requirement essential for the proper operation of a diagnostic system is the proper execution and adherence to fundamental prerequisites, which include selecting appropriate diagnostic procedures, possessing knowledge and proficiency in equipment operation, and accurately processing and generating output values.

The present study endeavors to elucidate the offline diagnostic techniques of the induction motor, particularly regarding the examination of discrete components, focusing on detecting faults in the rotor. Henceforth, including further connections is ordinarily disregarded, except for explicit connections about asynchronous motors.

2.4 Typical Faults in Induction Motors

As mentioned in chapter one, provided a brief overview, the faults have been classified into two principal groups: mechanical and electrical. Moreover, the typical faults mainly occurred in the stator and rotor parts in the IM.

2.4.1 Stator Faults

The stationary component of an asynchronous machine, known as the stator, represents a supporting frame, magnetic circuit, bearing shields, and terminal block. Different materials can be employed in the frame's construction, including cast iron, welded materials, or aluminum. The stationary magnetic circuit comprises sheets that are electrically insulated from each other and are compressed into the case, taking the shape of an enclosed machine. The stator winding, commonly composed of a three-phase system but may consist of varying phases, is situated within the recesses of the plates. The terminals of the windings are typically situated on the framework and are utilized to establish a power connection. These terminals are commonly arranged on a terminal strip, facilitating integration with a power source.

In most instances, stator defects are causally linked to malfunctions in the stator winding. One prevalent cause of winding faults in electrical systems is the ruptured insulation of the conductors. This malfunction often leads to a short circuit between the conductors, a short circuit between phases, between conductors within a single phase (known as inter-turn faults), or a short circuit between one or multiple phases and the earth. Insulation experiences deterioration over time due to natural aging. However, exposure to deleterious external factors can significantly hasten the degradation process and reduce its lifespan.

Thermal stress is a predominant external strain that holds a significant important position. When choosing insulation for a specific use case, it is essential to consider the heating effects associated with the nominal machine load for which the insulation is intended, the financial considerations, and the prevention of undue wear and tear. When the machine is subjected to overload, a temperature rise is observed because of the current flow that exceeds its capacity, consequently leading to the overloading of insulation. According to a report referenced as [9], the insulation's lifetime can be reduced by up to half due to thermal aging resulting from excessive overheating, even by a marginal increase of as low as 10 °C. This is with simultaneous diminution of the insulation's ability to withstand the nominal temperature. Based on adverse conditions concerning the longevity of winding insulation is the repeated operation of the machine, without any intermittent halting for cooling.

One of the negative external factors is electrical stress. Overall, it can be posited that the preeminent electrical stresses are transient and arise in response to transient events and an abrupt perturbation in voltage over a relatively brief period. Considering the proliferating employment of soft-start inverters, optimizing the output of the inverter modulation process involving orthogonal voltage pulses is imperative. This necessitates minimizing the duration of the rise of said pulses despite the inherent constraints stemming from switching losses exhibited by the semiconductors utilized. The motor receives an input that can result in recurrent voltage spikes generated by the inverter. However, if these spikes surpass the repeatable threshold of the dielectric strength of the insulation, there is a possibility of reduced service life for the equipment. A comparable scenario is linked to motor circuit breakers, capacitors, or diverse short-circuit deviations within the context under consideration.

Mechanical stress resulting from the collision of a rotor with a stator due to the failure of a partial component, such as a bearing or shaft, is rare. However, such events can cause significant damage to both components. The integrity of the insulation may be compromised because of the uncontrolled movement of a rigid, metallic component that has broken off from an internal component of the equipment.

External contamination-induced stress occurs when foreign particles, including water and dust, infiltrate a system. Research suggests that the stresses can be reduced by implementing appropriate handling procedures, adequate coverage during the application, and routine inspection, maintenance, and cleaning practices [16].

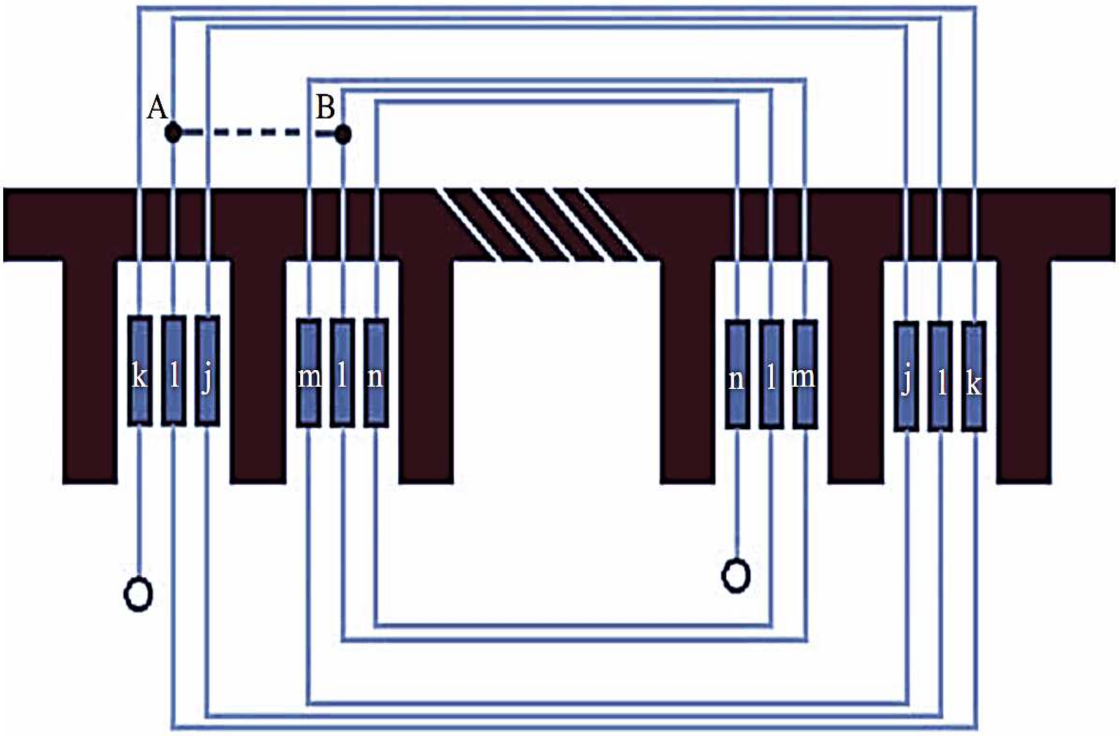


Figure 2. 2: The distribution of windings in the occurrence of an Inter-turn Short-circuit [16]

2.4.2 Rotor Faults

The rotor of an asynchronous machine comprises a shaft, a set of mutually compressed insulated plates that collectively constitute the magnetic circuit of the rotor, and a winding. The rotor's winding may be coiled within grooves, like the stator, and extended onto rings. This type of structure is commonly denoted as wound armature in academic discourse. Typically, a rotor featuring a cage configuration is commonly employed in engineering applications instead of a wound rotor. This rotor design typically entails the utilization of aluminum bars, which are fixedly interconnected at their extremities using shorting rings. In high-power motor applications, copper is commonly utilized as the material for both the rods and rings. Subsequently, the rods are securely integrated within the grooves on the equipment shaft's plates. The occurrence of malfunctions in rotating machinery can be attributed to various reasons, including the structural composition of the rotor. Specifically, the failure of the rotor may result in bending or misaligning of the shaft, referred to as eccentricity, as well as any damage inflicted upon the rotor wires or shorting rings.

The phenomenon of rotor misalignment in the stator is known as eccentricity. Therefore, the airgap around the rotor circumference is not symmetrical [18]. There are mainly three types of eccentricity these are static and dynamic or mixed eccentricity faults [13].

Figure 2. 3: The faults of Static and Dynamic Eccentricity [13]

2.4.3 Bearing Faults

Electric machines that rotate and seek to minimize friction and noise in the process of shaft motion utilize bearings. Bearings can be classified into three distinct categories: plain bearings, rolling bearings, and magnetic bearings. One of the most prevalent types of bearings utilized in various applications is rolling bearings, with a particular emphasis on ball bearings. The parts of a ball bearing include an outer and inner ring, a cage, and rolling elements, specifically balls. All the components, excluding the ball cage, are susceptible to deterioration caused by abrasion of the materials, mechanical wear and tear, and extrinsic factors. The notion that external factors may be regarded as internal strains or oscillations bears relevance in academic discourse. Bearing defects may arise due to bearing currents or mechanical stresses while undergoing rotational motion [13] [15].

The phenomenon of bearing currents is attributed to shaft stresses, which can manifest either between the extremities of the shaft or against the ground. For bearing currents to flow, it is imperative to exceed a specific voltage threshold that disrupts the lubrication layer within the bearing. Various factors can precipitate stress on the shaft such that,

- *Inducing an electromotive force by the alternating component of a pulsating magnetic field at a particular location can be referred to as induction.*

- *By an asymmetric electric or magnetic circuit.*
- *The static charge on the rotor in various machines, such as turbines and compressors.*
- *The cause of insufficient insulation.*
- *Increase in stator voltage gradient on certain occasions.*

In the presence of parasitic currents, capacitances between machine components or between the machine and the ground may become subjected to stresses caused by frequent fluctuations in voltage. The technique is currently relevant due to the prevalent utilization of solid-state converters to power asynchronous motors.

The detrimental effect of currents in the bearing manifests typically at the juncture of the rolling elements and the orbital tracks of the inner and outer rings. This deleterious impact is audibly perceptible in the form of amplified noise. Identifying the specific causative factors responsible for the degeneration of bearings poses a formidable challenge and frequently necessitates microscopic scrutiny. An additional potential failure mode of bearings is ascribed to the mechanical wear witnessed in the constituents of the balls or the inner and outer rings brought about by the rotation of the rotor, according to scholarly sources [9] [13].

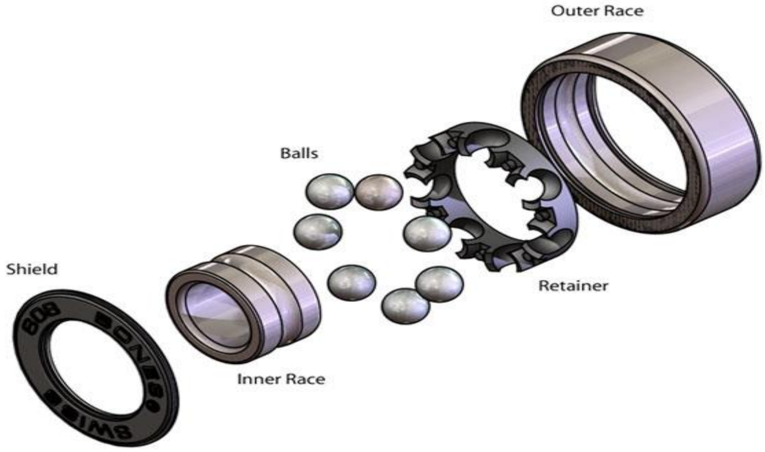


Figure 2. 4: The Parts of a Bearing [19]

2.5 Diagnosis of the Asynchronous Machine Faults

Diagnosis means that it is related to penetrating the problem to get knowledge. Fault diagnosis assumes that a fault has already happened in a device, while the final goal is to detect the fault with an appropriate diagnostic procedure. In electrical machines, a fault will automatically create an asymmetry in the magnetic field. This asymmetry will pass on to electromagnetic variables like currents, voltages, magnetic flux, electric and mechanical power, torque, and speed. So, the diagnostics engineer needs to monitor and analyze some of the above variables and detect any divergence from the expected healthy machine characteristics [13].

The field of fault diagnosis for electrical machines has observed notable progress through the sustained research efforts of specialized domains. The supervision of electrical machinery with the objective of diagnostic evaluation and anticipation of potential deficits has stimulated numerous scholarly inquiries owing to its significant impact on the public execution of diverse industrial processes.

Efficient diagnosis and prompt fault detection are essential factors that help minimize the respective industrial procedure's downtime and maintenance duration. This finding suggests that the negative consequences of these inadequacies, which can sometimes result in severe economic implications, can be prevented. Consequently, the probability of financial difficulties can be reduced.

An effective sound detection protocol should encompass fundamental minimalistic steps pertinent to the concerned process, coupled with the acquisition of a comprehensive diagnosis that unequivocally delineates failure modes through a time-limited analysis of data [13].

2.6 Types of Diagnostic Methods

The categorization of diagnostic investigation can be divided into two primary categories based on the methodology employed. Specifically, online (functional diagnostics) and offline (test diagnostics) represent the two fundamental approaches utilized in the field. The former is conducted while the system operates, whereas the latter is performed when the system is not in use.

2.6.1 Online Diagnostic

Online diagnostics utilizes the inherent involvement of the diagnosed entity in the operational process, allowing for a thorough examination of the system's dynamics. In the realm of online diagnostics, the strategic installation of sensors within the internal environment of the engine facilitates a continuous or periodic collection of pertinent data, thereby enabling instant evaluation of the machine's state. Typically, equipment designed for online assessment of an object's condition is fully automated, enabling the user to promptly procure status updates regarding the machine through information directly obtained from the system. The practice of operational diagnostics identifies mechanical irregularities, including but not limited to rotor defects or other dynamic elements. The detection process often necessitates examining various diagnostic indicators, including the magnetic field in the air gap (which may undergo deformation in the presence of faults), vibration patterns, and stator current behavior. Henceforth, it is conceivable to discern any malfunctions that lead to creating a distinctive pattern within a designated amount, such as its temporal progression. Online diagnostics serves as a key tool for identifying various malfunctions in electric motors, including but not limited to eccentricities, loose stator windings, and deformation of rotor bars and bearings [16] [17]. A typical online condition monitoring system process is shown in Figure 2.2.

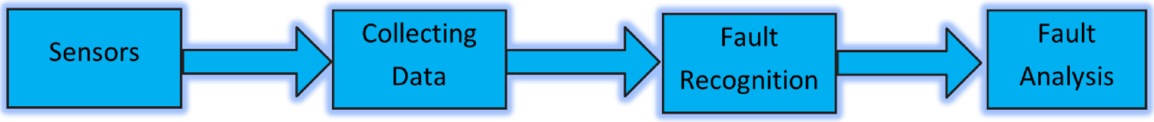


Figure 2. 5: Online Diagnostic Monitoring System [17]

2.6.2 Offline Diagnostic

Offline diagnostics are conducted in the event of a fault or during scheduled maintenance machine shutdowns. Offline diagnostics are commonly used for static tests on various machine components, including stator and rotor windings. Testing procedures can be performed utilizing both high and low-voltage supplies. The primary objective of said testing is to identify heightened resistance, such as malfunctioning rotor bars, subpar contact, or harm inflicted upon components such as conductors located within the grooves. The detection of diminished insulation capacity is also a possibility. An inherent limitation of offline diagnostics is that it necessitates the removal of the machine from service, thereby precluding the testing of the object in its authentic operational environment. On the contrary, offline diagnostics portray a greater degree of dependability than online diagnostics since the outcomes of the latter may be influenced by operational factors such as network and load [16] [17].

2.7 Offline Diagnostics in Asynchronous Machine Manufacturing

Offline diagnostics pertains to scrutinizing data obtained from a system or machine after its cessation or disconnection from a network. This may constitute information derived from a diverse range of sensors, logs, and supplementary resources obtained during the system's functionality. The objective of offline diagnostics pertains to identifying potential concerns or domains that necessitate enhancement in the performance or conduct of a system without the need for the system to be functional or interrupt its functioning. This functionality can prove beneficial in identifying and resolving issues that may not be readily discernible during standard operations or in enhancing the efficiency of a system through continued optimization. Offline diagnostic techniques are frequently implemented within industrial and manufacturing environments to monitor and enhance the operational efficiency of machines and processes. Nonetheless, such methodologies can also prove helpful in diverse situations, ranging from software debugging to system maintenance.

During typical operations, systems can generate significant amounts of data from several sensors, logs, and other pertinent sources. Notwithstanding, the task of real-time data analysis may prove to be challenging, mainly when dealing with intricate systems or systems composed of various interrelated components. In contradistinction, offline diagnostics allows a comprehensive examination and later evaluation of the collected data. At the same time, the system is disconnected from its operational state, thus allowing for a more nuanced and precise assessment of the system's level of performance and behavior.

Offline diagnostics possess significant utility in industrial and manufacturing settings, as they aid in observing the efficiency, safety, and conformity of machines and operations. If a machine experiences an unexpected cessation of operation, employing the technique of offline diagnostic analysis may serve to ascertain the underlying cause of the malfunction and enable timely remediation measures to be carried out. Similarly, offline diagnostic methodologies, for instance, electromagnetic testing procedures, can identify irregularities in the rotor of an asynchronous mechanism when online monitoring systems are either unattainable or financially impractical [13].

The offline diagnostic serves as a crucial instrument in identifying and resolving complexities in intricate systems, thereby facilitating the optimization of their performance over time. This methodology facilitates an accurate and precise examination of system conduct without impeding its functionality. It can be implemented in several domains, such as manufacturing, software engineering, and maintenance.

3 Rotor Faults Diagnostic Methods and Processes

Efficient diagnosis of issues and prompt recognition of faults are conducive to diminished periods of inactivity and shortened duration of maintenance in the proper industrial operation. This suggests that the adverse consequences, on occasion resulting in disastrous outcomes stemming from such inadequacies, can be prevented, thus reducing the probability of financial difficulties.

A sound detection protocol must encompass appropriate minimalist measures relevant to the process at hand, alongside acquiring a diagnosis that unambiguously identifies the failure modes via analysis of the available data within a specified timeframe. The most used methods for detecting rotor faults are described briefly in this chapter.

3.1 Methodology of Asynchronous Motor Diagnostics

The diagnostic process for an asynchronous motor, regardless of the specific fault detection method employed, can be generally delineated into three essential steps [21]-

- *Measurement and preprocessing of the signal of the diagnostic variable*
- *Generation of diagnostic symptoms*
- *Evaluating the symptoms and generating a diagnosis*

3.1.1 Measurement and Signal preprocessing

Numerous types of sensors are utilized to acquire the diagnostic signal, whereby a diagnostic parameter (such as voltage, current, vibration, or temperature) is converted into an electrical signal that can be recorded and analyzed. Typically, after the initial measurement, the electrical signal is subject to filtration and conversion into digital format through a transducer. Subsequently, the pre-processed signal is utilized as an initial variable to produce diagnostic manifestations.

3.1.2 Generating Diagnostic Symptoms

Diagnostic symptoms can be produced through a variety of distinct means, including -

- *Through Signal Analysis*
- *By using Diagnostic Models or*
- *Based on Investigational Information*

3.1.2.1 Determination of Fault Symptoms based on Signal Analysis

The predominant approach for ascertaining diagnostic indications involves deconstructing the diagnostic parameters collected from machine functioning into a frequency distribution. As previously stated, the spectral decomposition method commonly employs gathered stator voltages, currents, and magnetic flux present in the air gap or vibrations. Using frequency decomposition, it is theoretically feasible to identify electrical anomalies of both mechanical and magnetic origin and detect disparities present in electrical or magnetic circuits. The adverse circumstances referred to are evidenced in the spectrum by the emergence of indications of a specific scale (namely, the amplitude within the frequency spectrum) at the relevant frequency point. Every disruption generates a unique signature characterized by distinct frequency and amplitude values, thus enabling the differentiation of discrete disturbances. This method allows for the precise identification and separation of individual perturbations. The spectral decomposition process can be executed in real-time, whereby the diagnostic system does not necessitate the generation of a distinct input signal. Instead, the system merely employs the pre-existing variables as the equipment operates. An alternative approach entails acquiring the signal during the operation of the device and subsequently performing a conversion of the signal from the time domain to the frequency domain with the aid of appropriate software [21].

3.1.2.2 Identification of Symptoms of Disorders using a Diagnostic Model

Many diagnostic methods use algorithms to create diagnostic symptoms of disorders using models. Such methods are based on comparing data provided by the real diagnostic object and its corresponding model.

Although it is possible to look at the diagnosed object in different ways and apply to it many diagnostic methods, it is always necessary to start with a few basic steps. First, it is advisable to become familiar with the object to be analyzed to obtain information about its structure and operating environment conditions. From such knowledge, an approximate diagnostic model can then be derived, which is suitable both for studying the internal structure and for simulating the investigated, usually fault situations, which as an experiment, could sometimes be very or otherwise unfeasible. Modeling can therefore be understood as a simplified representation of the original object using a model to facilitate the description of an otherwise complicated original. Creating a model of a more complex system should be approached systematically, i.e., first model individual sub-models corresponding to specific subsystems and then build the corresponding system. The advantage of such an approach is a good description of more complex units and the possibility of dividing the system into fault-free subsystems and faults.

Diagnostic models can be divided into physical and mathematical. Physical models are material entities related to the modeled same physical or another analogous principle. On the other hand, mathematical models are more hypothetical, and a system of equations and inequalities usually describes the output quantities of the diagnosed object. They are further divided into analytical, logical, and topological models in this direction.

The suitability of using a particular model and the processing method is chosen based on sufficient knowledge of the diagnosed object and the nature of the measurable variables [15].

3.1.2.3 Generation of Fault Symptoms based on Investigational Information

Another critical set of diagnostic indications arises from heuristic information derived from experiential knowledge and practical judgment. The information is obtained by a human operator who frequently encounters the diagnosed entity. In typical practice, the operator retains knowledge regarding the machine's past operations and the conditions under which it functions. Primarily, the operator is equipped to perceive variations in the machinery's demeanor through human sensory modalities, including heightened noise levels, vibrations, temperature fluctuations, and odorous emissions. Consequently, such measures could facilitate prompt detection of potential hazards, circumventing untoward occurrences [15].

3.2 Commonly used ASM Diagnostic Methods

An appropriate methodology should possess the capacity to promptly identify faults, enabling the timely detection of individual defects to preclude occurrences of machine collisions. The identification of subtle faults through diagnostic variables necessitates the demonstration of significant changes.

Signals that change only very slightly in the presence of a fault are, therefore, unsuitable for diagnosing the fault.

Using equipment with the highest possible accuracy for signal processing or evaluation is always essential. However, it is advisable to prefer signals that do not require too high an accuracy for processing and always reliably indicate a fault.

Methods or ways of diagnosing individual asynchronous machine faults there are countless. Each method has its specifics and, therefore, different applications. The elemental classification of diagnostic techniques is derived from the location of the source of the failure. These methods detect malfunctions in the stability and rotor components of asynchronous machines.

Nevertheless, intricate techniques can be employed to uncover faults occurring in the stator and rotor simultaneously. Among these techniques are vibration analysis, air gap magnetic flux analysis, and signature analysis of stator currents, all representing practical diagnostic tools for assessing the performance of various electrical systems. The present procedures are categorized as online diagnostic methods. Due to their capability of detecting a wide array of faults, they are highly advantageous for practical purposes and are frequently employed. The prevalent technique employed for identifying faults is vibration spectrum analysis. However, its utilization can be hampered by the associated cost implications, primarily stemming from expensive accelerometers, making it less expedient. In contrast, the utilization of signature current analysis represents a straightforward and cost-effective approach that, when implemented with a thorough understanding of the underlying system, can yield precise and comprehensible findings [18].

3.3 Diagnostics Methods for Rotor Faults

The detection and identification of rotor faults are frequently achieved using large-scale online techniques, such as analyzing current signatures. Notwithstanding its universality and general appropriateness, the reality exists that in certain circumstances, this approach may fail to yield entirely precise outcomes. The signature method may not apply to machines that experience frequent load variations or operate at extremely low slip frequencies. In certain circumstances, the signature analysis may produce erroneous fault indications, particularly in situations involving low-frequency oscillations load or magnetic anisotropy of the rotor core.

When testing rotor faults, it is conceivable to utilize supplementary offline assessment, wherein the rotor is detached from the machine and subjected to distinct analysis. The approach's efficacy is fundamentally irrefutable, as any defects in the rotor are directly observed and remain unencumbered by extraneous influences. One possible drawback pertains to the essential cessation of operations and deconstruction of the device. Hence, it becomes apparent that conducting such evaluations can only occur through intermittent closures to facilitate examination-related activities or as a means of substantiating an alarming discovery utilizing internet-based techniques. A unique approach that is deemed more advantageous in the field of electrical machinery is the utilization of low-voltage single-phase rotational testing. This method eliminates the need for mechanical disassembly of the machine. The experimentation involves the application of a unipolar voltage source, operating at an approximate magnitude of one-fourth or one-eighth of the machine's rated voltage. Subsequently, the two motor phases are linked to the source's poles in an academic style of expression. When the rotor is manually rotated, the current measurement is conducted to identify faults in the rotor. In machine health, a consistent current display is an indicative marker of a well-functioning machine. However, in cases where there is asymmetry, the current values are observed to fluctuate [22].

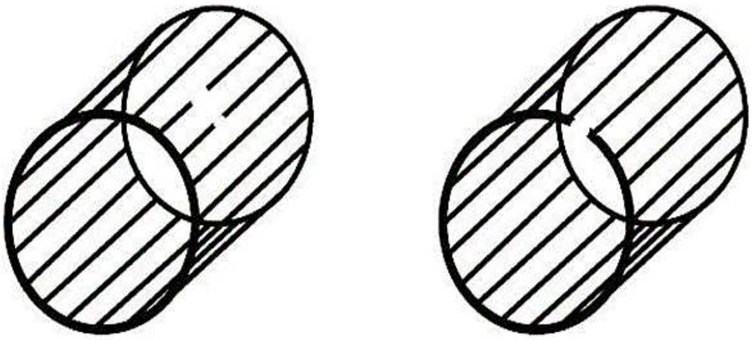


Figure 3. 1: Broken Bar and Short-Circuit Ring Breakage [3]

The asynchronous machine consumes a current multiple times its rated value during the start-up process. This occurrence can be advantageous for identifying discrete faults, such as broken rotor bars. As previously stated, during low-load operation, the manifestation of sidebands that signal a rod fault is either negligible or highly minimal. The significant advantage is that the inrush current exhibits a lower degree of sensitivity towards the load magnitude, in contrast to the current witnessed during engine operation. The facts constitute the fundamental tenet underlying the online run-active monitoring technique, which is concerned with procuring measurements of the current flow during the process of engine run-up. One potential drawback of this approach is that the measurements are limited to the initiation phase, thereby rendering the measurements relatively brief and temporally constrained. The start-up time of an asynchronous motor is contingent upon the inertia and load size, exhibiting a range from a fraction of a second for low-power equipment to a duration of multiple seconds for sizable and powerful machinery. Such variations are observed across operational conditions in asynchronous motor systems. One additional disadvantage affects the dynamic variability of rotor rotational speed, specifically during initiation, which subsequently induces corresponding fluctuations in frequency and magnitude indicative of a fault. Hence, it can be assumed that the method is of nominal significance, constantly fraught with inaccuracy.

The condition for utilizing the approach is that the commencement period must exceed no less than two seconds. It necessitates a straightforward start-up, wherein the motor is directly initiated from the primary power source. Furthermore, the monitored motor must not be subjected to variable torque loading. Subsequently, the run-up monitoring approach emerges as a viable supplementing methodology wherein the waveform is assessed utilizing a portable measuring unit that operates on an assuredly robust machine. Utilizing the obtained measured values, a comparison is performed between the current machine performance and previous start-up instances, whereby any indication of anomalous behavior is noted, regardless of its preliminary stage. The occurrence of faults in rotating machines is a function of several factors, among which the number of rotor bars holds significance. Specifically, when the rotor comprises many bars, any irregularity or disturbance in a single bar tends to have a lesser impact than in a system with fewer bars. The appearance of distortions at critical frequencies serves as an explicit indication of failures [23].

3.3.1 Failures of Rotor Bars and Shorting Rings

The rotor bars, interconnected by end rings, constitute a multiphase star circuit wherein individual bars contribute to distinct phases. The voltages on the individual bars conjoin to generate a symmetrical star concerning phases. Due to the tension present, a complex series of currents are induced within the cage, forming a symmetrical current system. Upon the commencement of an asynchronous motor, a significant surge current (frequently reaching magnitudes of up to 8 times the motor's nominal current) is transmitted throughout the apparatus, consequently exerting substantial mechanical strain on the constituent components of the rotor. The internal electromagnetic force experienced by the rotor from the system can be expressed through the subsequent Maxwell equations as,

$$F_{im} = \frac{1}{2}\frac{\mu_0 l}{b} i^2 \tag{3.1}$$

Where, μ_0 is the permeability of the vacuum (H/m), l is the length of the conductor (m), b *is* the width of the slot (m), and i is the current flowing through the conductor (A) [15].

The present failure can be attributed to the utilization of lower-grade materials, continuing overcapacity loading, or excessive initial exertion. In the context of rotor bars, a potential cause of failure is an elevation of the rod's resistance or a complete shearing and detachment of the component. The present trajectory. In this circumstance, the magnetic field produced by the currents of the rotor loses its symmetry. It impinges on the resultant magnetic field within the air gap of the apparatus, thereby causing deformation. The deformation of magnetic fields results in alterations of various quantities, including electrical, electromechanical, thermal, and acoustic parameters. Rotor bar failures are commonly associated with the degradation and elongation of motor start-up, parasitic moments, and a rise in thermal stresses in the unaffected portion of the winding. An uneven distribution of the total current among the bars in the event of a fault causes this phenomenon. The application of an electric current into the broken rod's circuit can initiate a transfer of electrical charge into the two adjacent rods, causing a significant increase in the level of mechanical demand placed upon them and the possibility of additional consequential damages to occur in other rods [15].

In every phase of the stator, the magnetic field in the gap induces a current, which goes through a specific displacement angle for each phase and is completed through the power supply network [18].

3.3.2 Eccentricity Fault in Rotor

Eccentricity refers to the non-uniformity of the air gap between the stator and the rotor, which arises from any of the following causes [13] –

- *The misalignment of the shaft arises from an imperfect coupling with the driven device.*
- *The misalignment of the rotor with respect to the stator is a critical issue that can impact a mechanical system's overall efficiency and performance.*
- *The phenomenon of bearing wear and its consequential effect on rotor misalignment.*

- *The execution of a process beyond the value of the critical speed.*

In significant eccentricity, the resultant radial forces, namely unbalanced magnetic pull, can potentially result in the rotor's friction against the stator. This, in turn, can lead to substantial damage to the machinery. From a reliability and performance optimization standpoint, it would be desirable if the machine were devoid of any anomalies. However, contemporary manufacturing techniques fall short of producing entirely flawless bodies. Hence the existence of eccentricities, even minor ones, cannot be mitigated. Hence, the complete exclusion of such imperfections remains elusive. A study referenced in [13] shows that eccentricities exceeding acceptable levels have been observed during the manufacturing process in as much as 10% of the cases. The rotor axis should be near and aligned with the stator axis for optimal machine performance. The categorization of eccentricities includes three distinctive types: static, dynamic, and mixed [3].

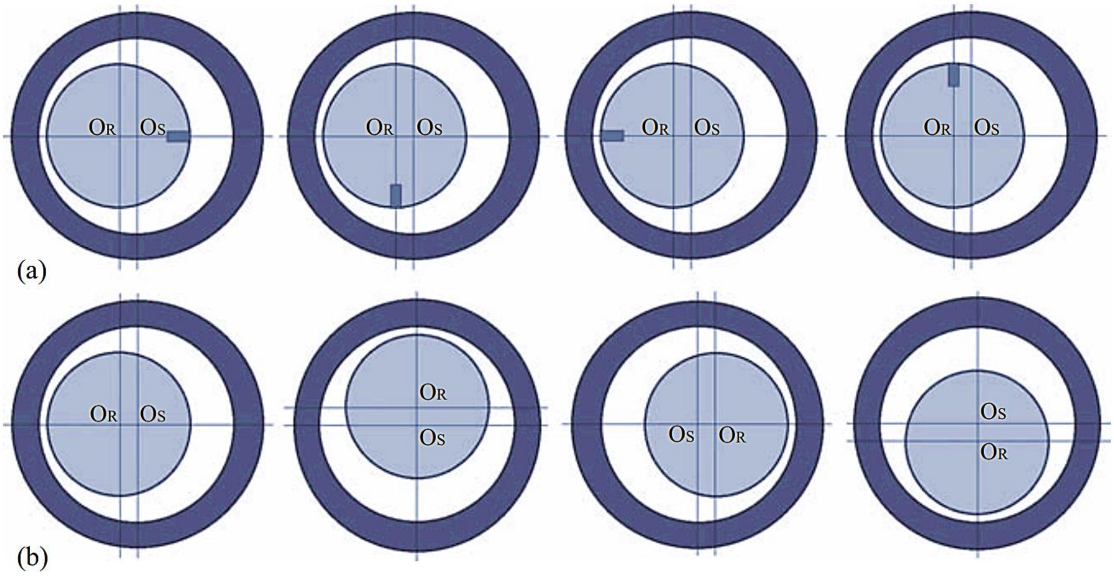


Figure 3. 2: Four Different of the Rotor Rotation for (a) Static & (b) Dynamic Eccentricity [13]

The static eccentricity phenomenon is characterized by a misalignment between the rotor axis of rotation and the primary axis of the stator, as depicted in Figure 4(a) [13] [15]. This misalignment leads to an uneven distribution of the air gap length within the machine. The scenario prompts a heightened degree of interaction between the magnetic fields of the stator and rotor that correspond to the shorter air gap, leading to the emergence of sidebands located at a distance from the fundamental frequency, f_1, and offset by the synchronous rotational frequency, $f_{sync.}$ as that [13] [15],

$$f_s = f_1 + f_{sync.} = f_1 + \frac{f_1}{p} \tag{3.2}$$

Static eccentricity is observed at a frequency that is twice that fundamental frequency. However, the identification of this condition is typically challenging owing to its association with the second harmonic of the main frequency, so that [13] [15],

$$f_{static} = 2 f_1 \tag{3.3}$$

Dynamic eccentricity refers to a state in which the rotor experiences a deviation from its initial axis of rotation while maintaining a symmetrical rotation relative to the principal axis of the stator (refer to Figure 4b). The length of the air gap is a function not only of the position of the rotor but also of the passage of time, as this variable length of the gap varies following the rotational speed of the rotor. For dynamic eccentricity, $f_{dynamic}$ is represented that [13] [15],

$$f_{dynamic} = f_1 \pm (1 - s) f_{sync.} \tag{3.4}$$

However, Induction motors (IM) can detect static or dynamic eccentricity faults. Utilizing monitoring the signatures present in the stator current at specific frequencies [13],

$$f_{ecc} = \left[(kR \pm n_d) \left(\frac{1 - s}{p} \right) \pm n \right] f_s \tag{3.5}$$

where R is the number of rotor slots, k is the integer coefficient, s is the slip, p is the pole pairs, n is the stator harmonic ranks, f_s is the supply frequency and n_d is an integer that can be zero for static eccentricity and non-zero for dynamic eccentricity [15]. Figure 3.3 shows the simulated normalized spectrum of the line current of a four-pole IM with 28 rotor slots under load conditions [13].

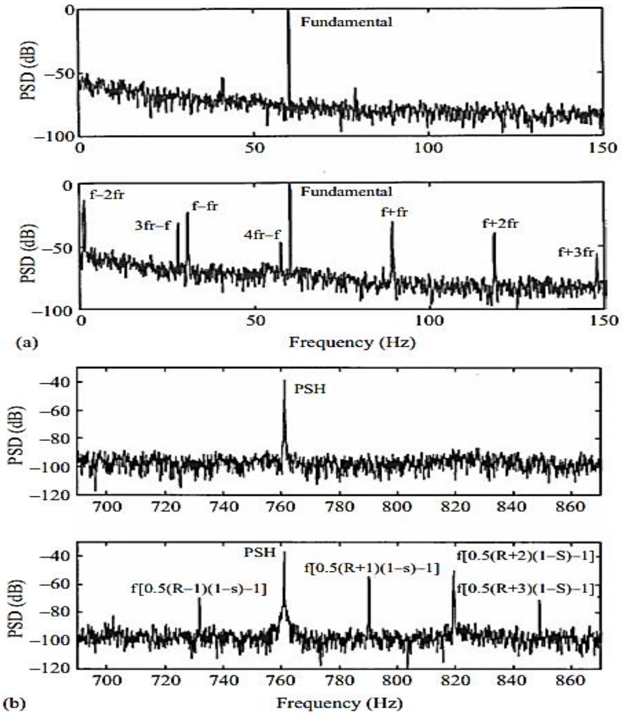


Figure 3. 3: (a) The Fundamental & (b) The PSH. Upper: healthy. Lower: with mixed eccentricity [13]

3.4 Typical Rotor Faults Methods

There are several commonly used rotor fault diagnostic methods in electrical machines, including-

- *Vibration Analysis*
- *Current Signature Analysis*
- *Motor Current Signature Analysis (MCSA)*

- *Magnetic Flux Analysis*
- *Airgap Monitoring Analysis*
- *Acoustic Emission Analysis*

3.4.1 Vibration Analysis

Vibration analysis is a widely used diagnostic method for detecting rotor faults in asynchronous machines. The method involves measuring the machine's vibration spectrum and analyzing the changes in the spectrum caused by the rotor faults. The changes in the vibration spectrum can be used to identify the type and severity of the fault.

The advantages of vibration analysis include its non-intrusive nature, low cost, and ability to detect a wide range of faults. However, the method has some limitations, including its sensitivity to environmental noise and the need for specialized equipment and expertise [24].

3.4.2 Current Signature Analysis

Current signature analysis is another offline diagnostic method for detecting rotor faults in asynchronous machines. The method involves measuring the machine's current waveform and analyzing the changes in the waveform caused by the rotor faults. The changes in the current waveform can be used to identify the type and severity of the fault.

The advantages of current signature analysis include its ability to detect early-stage faults and its sensitivity to specific types of faults, such as broken rotor bars. However, the method has some limitations, including its sensitivity to load and speed variations and the need for specialized equipment and expertise [25].

3.4.3 Motor Current Signature Analysis (MCSA)

The most popular technique is MCSA for detecting faults in IM. Motor current signature analysis (MCSA) is a variation of current signature analysis focusing on the motor current waveform. The method involves measuring the motor current waveform and analyzing the changes in the waveform caused by the rotor faults. The changes in the motor current waveform can be used to identify the type and severity of the fault.

The advantages of motor current signature analysis include its ability to detect early-stage faults and its sensitivity to specific faults, such as broken rotor bars. The method is also less sensitive to load and speed variations than the current signature analysis. However, the method has some limitations, including the need for specialized equipment and expertise. This research used MCSA to detect the Broken Rotor Bar faults.

3.5 Mathematical Representation of MCSA to Detect Rotor Asymmetry

Many techniques based on Motor Current Signature Analysis (MCSA) rely on identifying and analyzing specific frequency components that are indicative of faults in electrical machines. Harmonics exhibit the potential to facilitate an effective diagnostic process, possessing the capacity to identify underlying abnormalities accurately. The aim is to identify the irregularity in its emerging stage. Machine anisotropies, such as those reducing from constructional unbalance, can generate Principal Slot Harmonics (PSH) within the stator current spectrum. The next step is to convert the signal from the time domain to the frequency domain. This is usually achieved with a spectrum analyzer and an oscilloscope controlling the Fast Fourier Transform function (FFT) with suitable software.

Research has demonstrated the causal relationship between rotor asymmetry, specifically rotor bar failure, and the consequential emergence of a magnetic field that displays a differential rotational direction compared to the primary forward field. This distinct magnetic field is characterized by a slip frequency inextricably linked to the forward field. Furthermore, identifying of detecting rotor faults, such as high resistance connections, broken end rings, and Broken Rotor Bar (BRB) as following frequencies that [26],

$$f_{BRB} = f_s \pm 2ksf_s, \;\; k = 1, 2, 3, \dots \tag{3.6}$$

Where f_s is the supply frequency, s is the motor slip, and k is an integer representing the harmonics order coefficient. With increasing k coefficient, the harmonics frequency increases, but amplitude decreases. The first harmonics is the fundamental frequency to detect the BRBs.

3.6 Fourier Transform

The Fourier transform is an integral transform that converts a continuous signal between time and frequency domains. Each continuous periodic function can be decomposed into a unidirectional component by the Fourier transform the fundamental harmonic, and an infinite series of higher-order harmonic components described by the sine and cosine functions. Each component then has a specific amplitude and phase. The resulting series, the Fourier series, describes the relationship between the function under investigation in the time and frequency domain. We obtain a series of discrete frequency components in the frequency domain by applying the Fourier transform to a continuous signal with a repetition period T in the time domain. Fourier Series is as follows [15],

$$f(x) = a_0 + \sum_{n=1}^{\infty} \left(a_n \cos\frac{2n\pi t}{T} + b_n \sin\frac{2n\pi t}{T} \right) \tag{3.7}$$

$$a_0 = \frac{1}{\mathrm{T}} \int_{-\mathrm{T}/2}^{\mathrm{T}/2} x(\mathrm{t})\, \mathrm{dt} \tag{3.8}$$

$$a_n = \frac{2}{\mathrm{T}} \int_{-\mathrm{T}/2}^{\mathrm{T}/2} x(\mathrm{t}) \left(\cos\frac{2n\pi t}{T} \right) \mathrm{dt} \tag{3.9}$$

$$b_n = \frac{2}{\mathrm{T}} \int_{-\mathrm{T}/2}^{\mathrm{T}/2} x(\mathrm{t}) \left(\sin\frac{2n\pi t}{T} \right) \mathrm{dt} \tag{3.10}$$

Where, a_0, a_n and b_n Are the Fourier coefficients, n is the harmonic order, and T is the time of the signal repetition.

This approach involves dividing the scrutinized signal into segments and subsequently utilizing the Fourier Transform (FT) on each segment, as depicted in Figure 3.4. This method yields an enhanced temporal resolution. However, it is essential to note that the duration of the phenomenon warrants consideration [28].

The concept of time window dictates a definitive association between time and frequency resolution, whereby increasing the time window yields enhanced frequency resolution but diminished time resolution, and conversely, decreasing the time window results in improved time resolution but reduced frequency resolution. A signal $x[n]$ is given by [27] as,

$$x\ (m, \omega) = \sum_{n=-\infty}^{\infty} x[n]\left[w_f\right][n-m]e^{-\mathrm{j}\omega\mathrm{n}} \tag{3.11}$$

Where w_f is a window function, e.g., a rectangular window that is non-zero for only a short time, n and m are indices for the samples in the signals, and $e^{-\mathrm{j}\omega\mathrm{n}}$is the transformation sum.

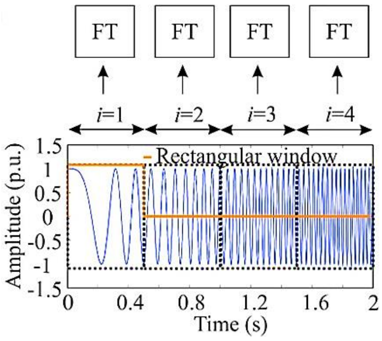


Figure 3. 4: Short-time Fourier Transform [28]

3.6.1 Fast Fourier Transform

The Fast Fourier Transform (FFT) is an established nonparametric technique that leverages signals from current motor data and is a general approach for detecting faults in the rotor bar. A singular BRB fault can be detected through frequency sideband monitoring of the motor current signal near its fundamental frequency, utilizing the Fast Fourier transform (FFT). The sidebands are particularly conspicuous during the motor's maximum load. The deficiency of the conventional Fast Fourier transform (FFT) approach is exposed in the absence of load conditions, as it is not capable of discriminating between a sound motor state and faulty states in the no-load condition. An additional concern associated with the conventional FFT technique is the complete dependence on amplitude and sideband frequency as discerning factors for identifying faults. It has been noted that in the presence of unbalanced voltage, the spectral patterns present in current motor analysis bear similarity to those inherent in the spectrum of BRB fault current. This creates a challenge in accurately discerning the nature of the fault. The Fast Fourier Transform performs poorly in analyzing motors operating under transient conditions [30].

During the process of diagnosing rotating machinery, it is observed that specific frequency constituents display a relationship with the mechanical constituents located within the equipment. The monitoring and measuring amplitude levels of spectra throughout a period have demonstrated its efficacy as a technique for detecting discrete components that require maintenance, such as gears or bearings. Moreover, this approach provides insight into the optimal timing for such interventions [29].

Figure 3. 5: Example of a Frequency Domain Spectrum [29]

Furthermore, in settings with high levels of acoustic interference, Fast Fourier Transform (FFT) analysis presents a viable method for quantifying sound pressure. Determining the specific frequency ranges that are of critical importance and identifying loud tonal components existing within noise emissions empowers engineers to implement appropriate measures to reduce them [29].

4 FEM Electromagnetic Analysis of the Rotor

This chapter has described the fundamental process of 2D FEM Electromagnetic analysis of along with ANSYS® Maxwell-2D® and RMxprt® software tools used to create a squirrel cage motor design and analyze the effects of some specified faulty conditions. Alongside this, significant progress has been made in enhancing the efficacy of induction machines (IM).

However, diagnostic procedures primarily focus on material science and advancements in production techniques. Using computer modeling tools holds significant promise in predicting the motor's functionality before production. The tools facilitate expeditious and cost-effective iterations in design, facilitate the development of novel designs, and enable a comprehensive understanding of performance deterioration caused by defects. The parameters and characteristics of a motor can be precisely computed and anticipated using field computation and analysis findings.

4.1 Diagnostic Method for Rotor Faults

Diagnostic techniques founded upon the principles of Faraday's law of electromagnetic induction, which utilize both alternating and direct current to trigger the magnetic field, display great potential. Diagnostic systems commonly feature a sensing coil employing an inductive sensor or a Hall probe [32], [33].

The exciter for the magnetic field is positioned near the rotor and detects the constituent segments of the stray magnetic field via the employment of a Radio Magnetic Field Coil (RMF). The rotor generally remains stationary or experiences gradual rotational movement around its axis of rotation. Permanent magnets can induce magnetic field excitation [32], [33], as shown in Figure 4.1.

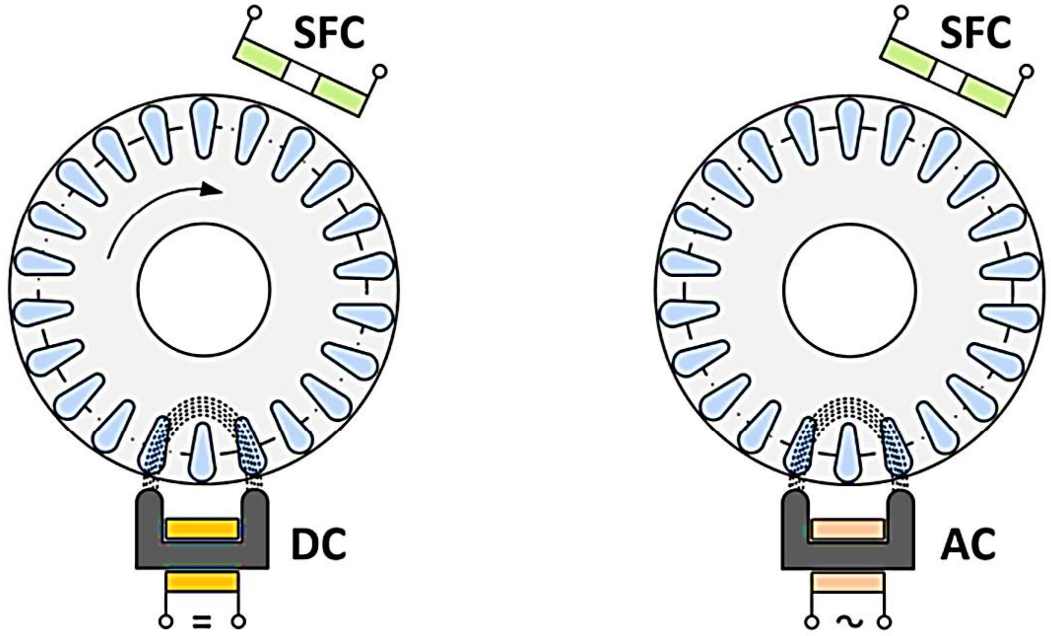


Figure 4. 1: Principle of Measuring Rotor Defect [34]

The diagnostic system utilized in this study is founded on the principle of a stationary magnetic field, where the rotor undergoes gradual rotation. An inductive sensor is utilized to detect variations in the magnetic field, and this sensor captures adjustments in the stray magnetic field adjacent to the rotor. The squirrel cage rotor's windings comprise electrically conducting bars interconnected at their ends by conducting rings. The rotation of the rotor in the presence of a consistent magnetic field denoted by flux lines induces the displacement of the bars, thereby causing a proportional alteration in the respective surface area. This phenomenon can be observed in the context of specific physical systems. The bars delineate the enclosed region through which the magnetic field completes a closed loop by Faraday's Law.

The fundamental idea of the measurement system is illustrated in Figure 4.2. In the magnetic field of the exciter, if rotor bars present defects such as bubbles, dirt, material inhomogeneities, or cracks in the bar, the form and amplitude of the voltage generated by the sensor show this symmetry. When there are significant defects, such as bars showing cracks, part of the induced voltage waveform will be completely absent. The amplitude and shape of this voltage are linearly related to the mechanical condition of the rotor [33] [34].

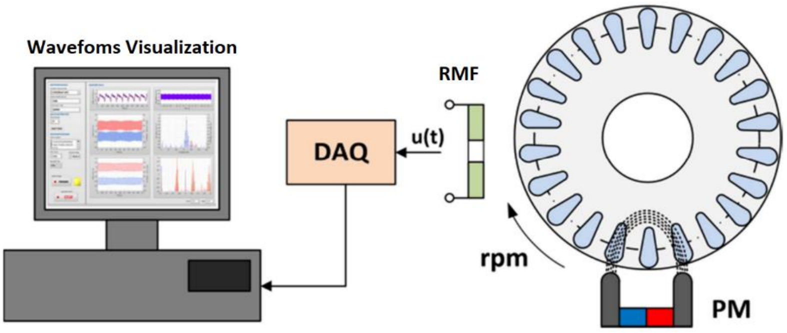


Figure 4. 2: Rotor Fault Detection System [34]

4.2 Finite Element Method (FEM)

The Finite Element Method (FEM) is a numerical technique that approximates the solutions to partial differential equations (PDEs) and integral equations. The method is used in various fields, such as engineering, physics, and mathematics.

The idea behind FEM is to divide a complex domain into more minor, more straightforward elements, where a set of equations can describe the behavior of each element. These equations are then assembled into a more extensive system of equations that describes the behavior of the entire domain. The resulting system of equations can be solved using numerical methods to obtain an approximation of the solution to the original PDE.

The FEM is beneficial when dealing with complex geometry and boundary conditions that cannot be easily solved using analytical methods. It is also versatile enough to handle various physical phenomena, such as heat transfer, fluid dynamics, and structural mechanics [31].

In practice, the FEM involves several steps, including mesh generation, element formulation, assembly of the element equations into the global system, and solution of the resulting system of equations. The solution's accuracy depends on the mesh's size and quality, the order of the element approximation, and the numerical method used to solve the system of equations.

4.3 Motor Design with ANSYS RMxprt® and Maxwell®

The ANSYS Maxwell® software is a commercially available electromagnetic field simulation tool used by engineers designing and analyzing various electromagnetic and electromechanical devices. These devices may include motors, actuators, transformers, sensors, and coils, among others, and may be developed in either 3D or 2D geometries. RMxprt®, a commercially available tool developed by ANSYS, is a template-driven electrical machine design software designed to facilitate rapid analytical calculations of machine performance. Moreover, this tool provides a comprehensive platform for creating 2D and 3D geometries, which can be utilized for detailed finite element calculations in ANSYS Maxwell. Apart from furnishing conventional motor performance computations, RMxprt® can produce an exhaustive translation of 3D or 2D geometry, encompassing all characteristics, to Maxwell for detailed finite element analysis assessments. ANSYS Maxwell® software has attained significant prominence and has become ubiquitous within relevant industries.

4.3.1 Squirrel Cage Motor Design with RMxprt®

A squirrel cage motor is conventionally manufactured with a laminated iron rotor interspersed with cast aluminum or copper. The preponderant portion of the rotor currents traverses the bars and insulated laminates. In the context of rotors, it is common for bars and end rings to exhibit low voltage levels and high current intensities. Such characteristics are often obtained by minimizing rotor resistance. Copper is commonly employed in high-performance motors to enhance their efficiency.

By using RMxprt, a 10kW three-phase squirrel-cage induction motor is designed. The parameters of the motor are given in Table 4.1.

Parameters	Dimensions
Number of Stator Slots	48
Stator Outer Diameter	264mm
Inner Diameter of Stator	170mm
Length of Stator	138mm
Number of Rotor Slots	28
Rotor Outer Diameter	100mm
Rotor Inner Diameter	34mm
Length of Rotor	140mm
Number of Poles	4
Voltage	400V, 50Hz

Table 4. 1: Motor Design Parameter

M36-24G material is assigned for laminated steels of the rotor and stator. The rotor bars are selected as aluminum, the windings are copper, and the shaft is assigned as magnetic shaft. The user interface of RMxprt is shown in Figure 4.1.

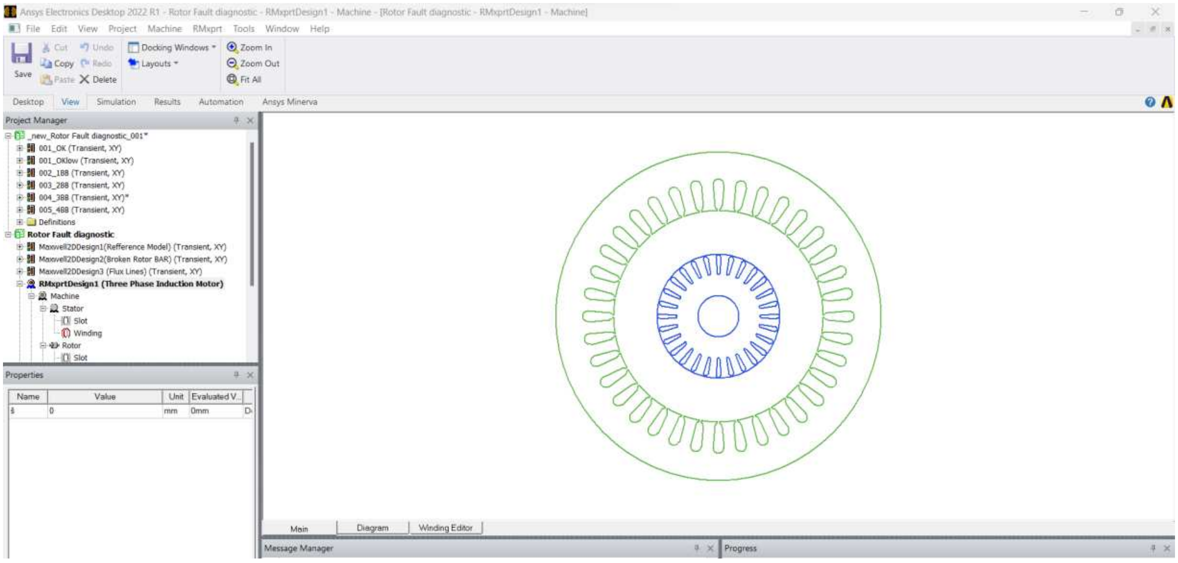


Figure 4. 3: Motor Design in RMxprt®

4.3.1.1 Simulation Results

The RMxprt is a template base tool; the time required for analysis is finished by several minutes. The results are presented in Table 4.2.

	Results
Rated Speed	1449.68 rpm
Stator Phase Current	4.30 A
Stator Resistance	0.39 Ω
Rated Torque	65.87 N-m
Total Losses	1424.68 W
Power Factor	0.93
Efficiency	87.54 %
Output Power	10.0006 kW

Table 4. 2: Simulation Results of Designed Motor

4.3.2 FEM Rotor Model with Maxwell 2D

The rotor in the given context is migrated to Maxwell software utilizing a direct interface from RMxprt. This approach facilitates seamless and efficient data exchange between the two tools for conducting comprehensive rotor analysis. Maxwell utilizes the precise finite element technique for resolving electrostatic, electromagnetic, and electric fields characterized by frequency and varying over time. The fundamental instrument for designing the configuration of the static field excitation and stray flux coil sensor. The numerical model is representative of its geometric, dimensional, and material properties.

In this study, provided on the user interface of Maxwell 2D and the rotor geometry are shown in Figures 4.2 and 4.3.

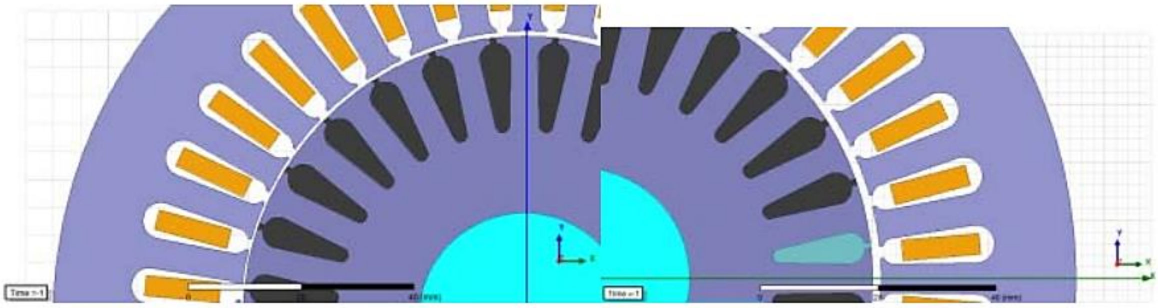
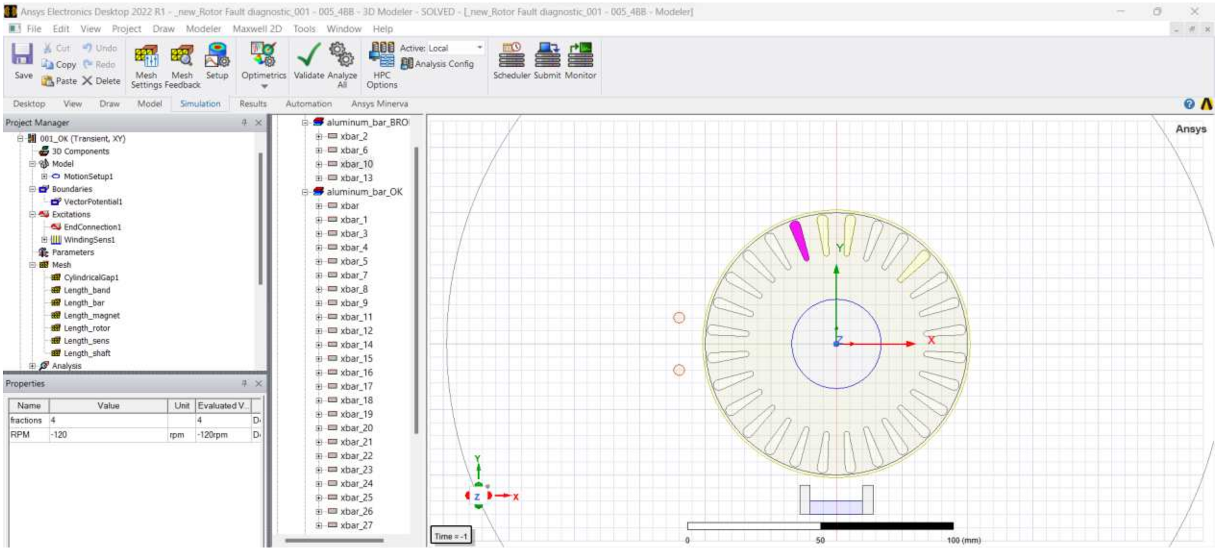


Figure 4. 4: Rotor Geometry in Maxwell 2D



Name	Value	Unit	Evaluated V…
fractions	4		4
RPM	-120	rpm	-120rpm

Figure 4. 5: Maxwell 2D Design

The present model incorporates a magnetic field excitation system, implemented through a permanent magnet and pole extenders, to relate the parameters to the rotor. A sizable air gap separating the rotor and exciter elements permits unhindered rotation of the rotor.

The Radio Magnetic Field (RMF) coil is located on the left side of the rotor, and the 2D Mash of the FEM model with PM and RMF coil are shown in Figure 4.6. A constant speed of n=120rpm defines the rotation of the rotor. The FEM model contains approximately 21152 elements, and transient time domain analysis was used to solve it.

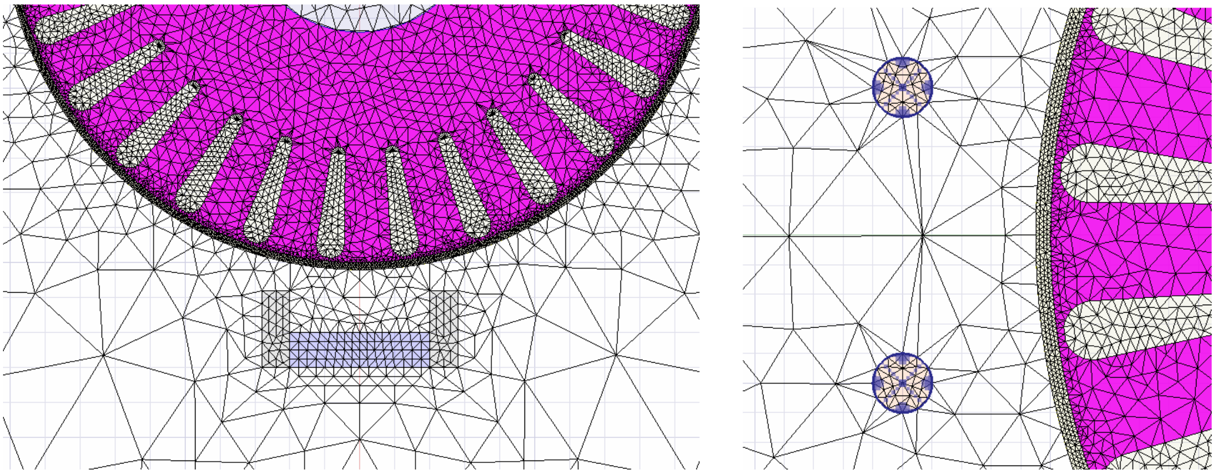


Figure 4. 6: 2D Mesh of FEM model of Rotor with PM & RMF Coil

4.4 Analysis of the Broken Rotor Bar

The analysis is performed with Maxwell 2D for a healthy rotor bar, one broken bar, one shorting ring, two broken bars, three broken bars, and four broken bars.

The main purpose of this analysis is to obtain and compare the variation of magnetic flux density of rotor teeth with healthy rotor bars. The graphical dependencies of the induced voltage in the RMF coil have also been obtained for FFT analysis. The simulation results were also compared with the practical measurements performed in the laboratory.

4.4.1 Simulation

The simulations are performed with a computer for which the specifications are listed in Table 4.3.

Specification	Processor	11th Gen Intel(R) Core (TM) i5-1135G7
	RAM	16 GB DDR4 3200MHz
	Graphics	NVIDIA GeForce MX350

Table 4. 3: Specifications of the Computer for Simulations

The five cases' magnetic flux density and field current distributions are considered. Firstly, the field shape for the healthy rotor without defects, then the deformation of the field lines when the cracked bar passes around the excitation yoke for simultaneously one, two, three, and four BRBs.

If the rotor bar has no faults, then the flux lines are forced out of the tooth space to the left in the direction of rotation. It is a situation where the reaction magnetic field generated by the current in the bar blocks the passing of field lines from the excitation. In contrast, if the bar is completely cracked or separated from the ring, the current does not flow through it, and there is no reaction magnetic field, which means that the rotor bar has lost its conductivity.

The flux lines are unrestricted in their movement and tend to form a closed circuit around the rotor tooth. The saturation level of the rotor tooth positioned at the excitation yoke is relatively higher.

Figure 4.7, the distribution of magnetic flux density and flux lines in rotor teeth for healthy rotor and BRBs.

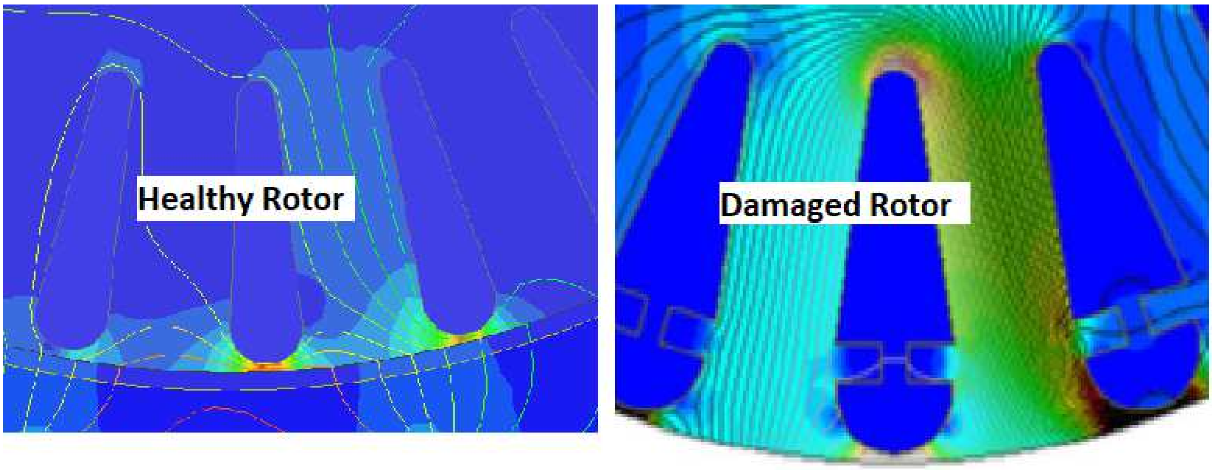


Figure 4. 7: Magnetic Flux Density & Flux Lines Distribution in Rotor Teeth

4.5 FFT Analysis of the Frequency Spectrum in Rotor Faults

Obtained results from Maxwell 2D are visual representation of the measurement results of the frequency spectrum of the RMF coiled voltages, as performed through FFT analysis. The present study presents a visual representation of the measurement results of the frequency spectrum of the external magnetic field, as performed through FFT analysis. The following figures provide a succinct illustration of these outcomes.

4.5.1 Effects in Healthy Rotor

The FFT analysis of the signal from the RMF coil. The transient waveform of the induced voltage from the RMF coil is shown in Figure 4.7. The voltage amplitude is normalized in the interval (-1,1). The time waveform of the voltage is not purely sinusoidal, it has shape distortion. The healthy rotor has a regular induced voltage waveform without deviations.

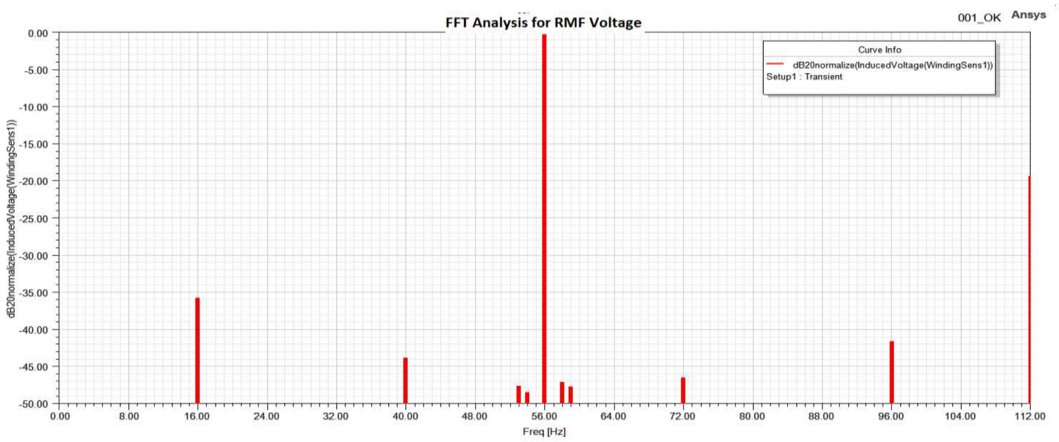


Figure 4. 8: FFT analysis of RMF induced voltage in model of Heathy Rotor

FFT analysis of the same signal in the normalized amplitude spectrum shows the fundamental frequency, f_s= 56Hz, which corresponds to the set rotating speed n= 120 rpm and the number of rotor bars N_R= 28. Other n-multiples of harmonics with frequency shift Δf= 16Hz are also visible. The Time domain analysis is also shown in Figure 4.8.

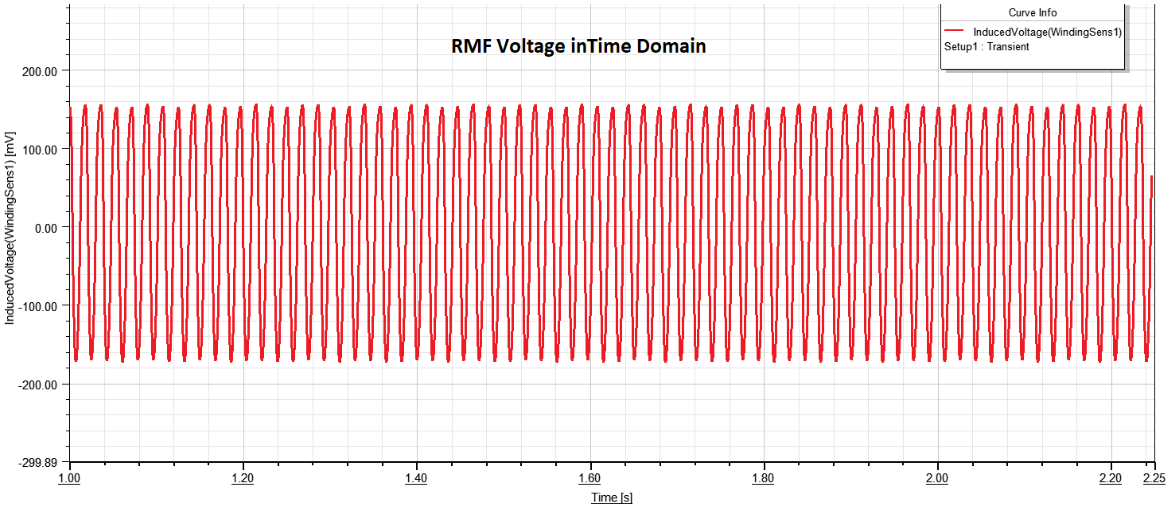


Figure 4. 9: Time Domain Analysis of Heathy Rotor

4.5.2 Effects in Defective Rotor Bars

FFT analysis and waveform of the induced voltage from the RMF coil when simulating fully broken rotor bar is shown in Figures. In that case some of the induced voltage is missing otherwise regular waveform represents. In addition, the bar faults also show an increased amplitude and delayed relatively long transient. Around the fundamental harmonic f_{BRB}= 56Hz, including their multiples, there is a dramatic increase in sidebands separated by Δf= 2Hz.

The FFT analysis of RMF induced voltage for one, two, three and four BRBs are shown that in Figure 4.10, 4.11, 4.12, and 4.13 respectively. In addition, the analysis of the short ring shows in Figure 4.14.

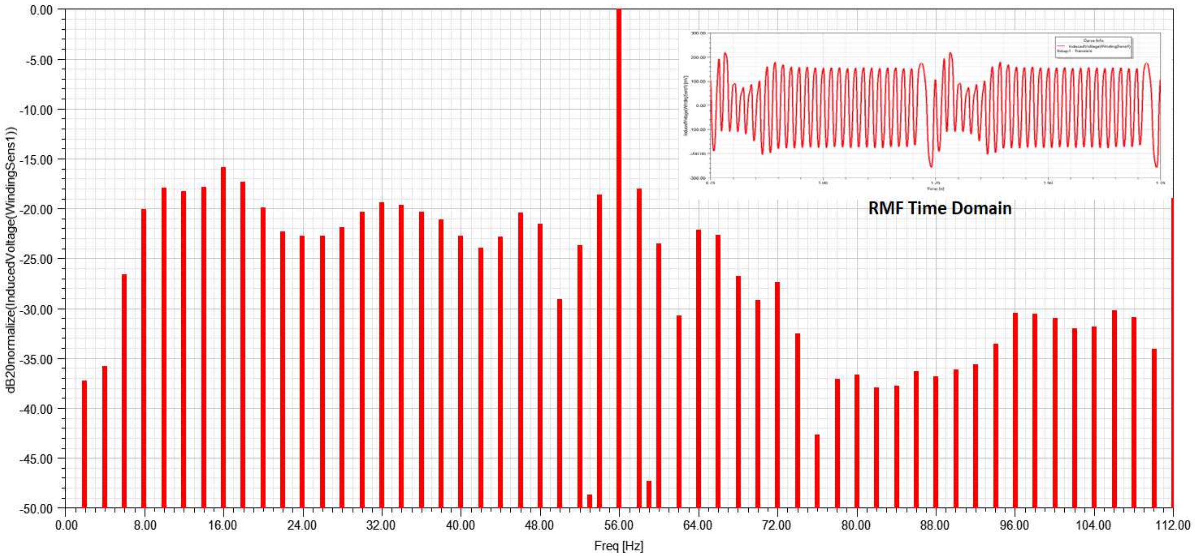


Figure 4. 10: FFT Analysis for One Broken Bar

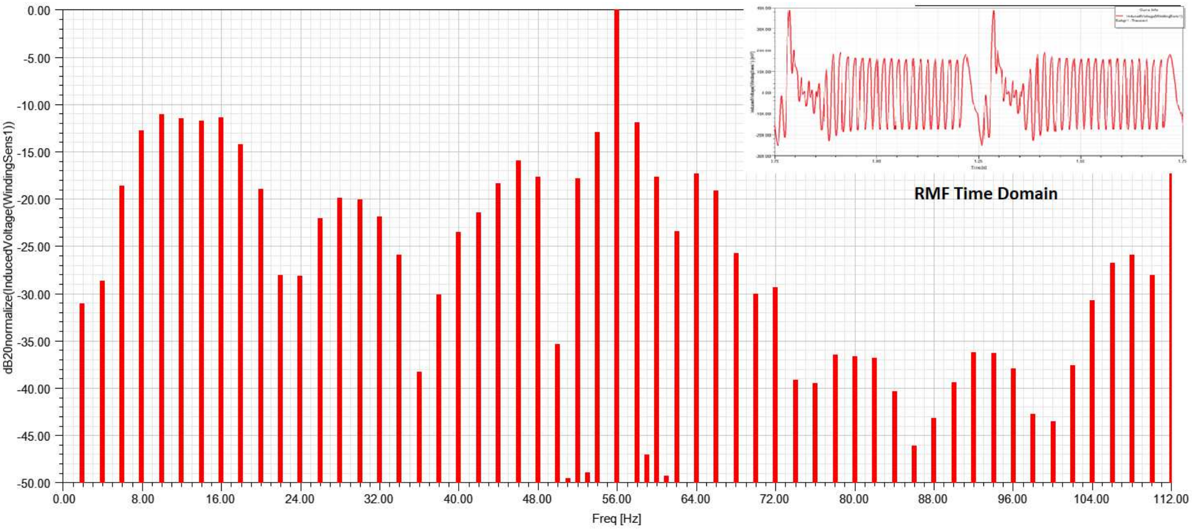


Figure 4. 11: FFT Analysis for Two Broken Bar

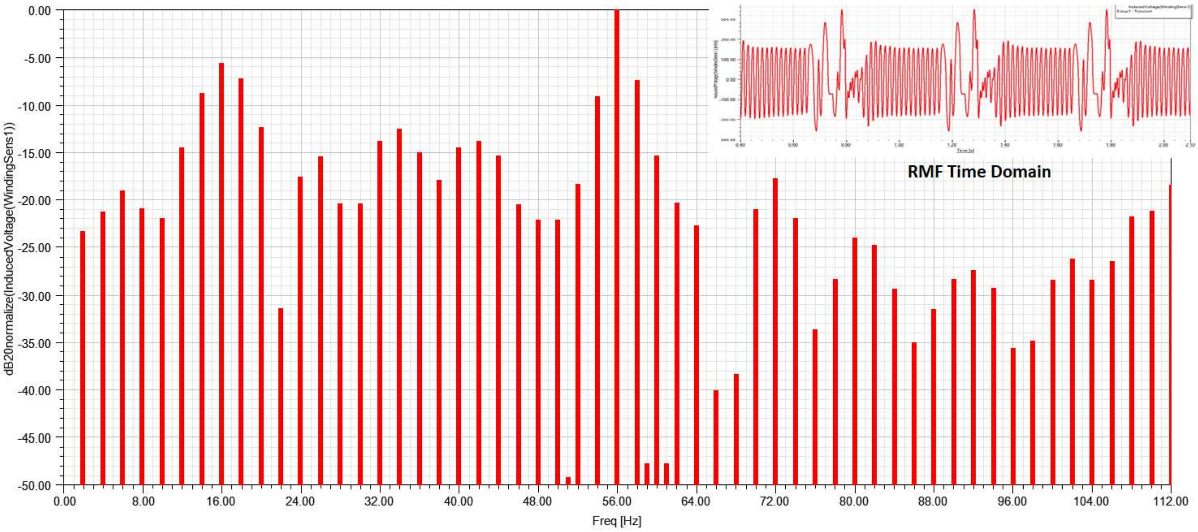


Figure 4. 12: FFT Analysis for Three Broken Bar

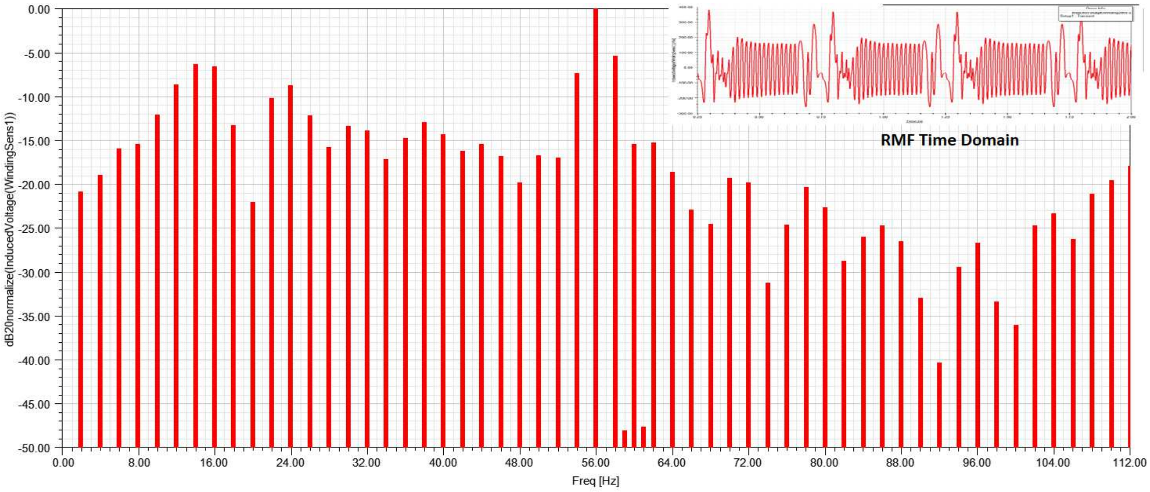


Figure 4. 13: FFT Analysis for Four Broken Bar

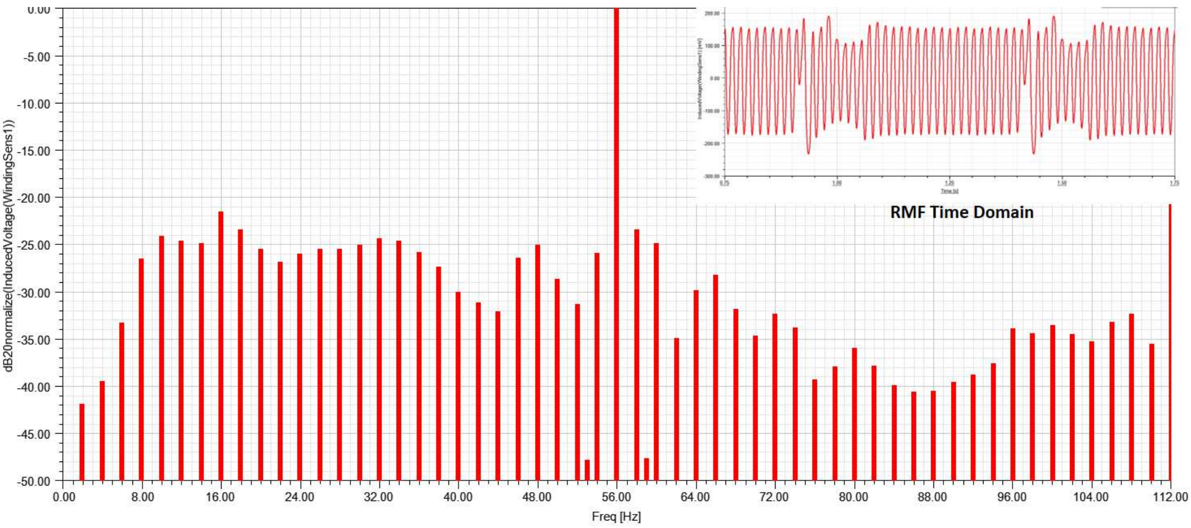


Figure 4. 14: FFT Analysis for One Short Ring

For one broken bar, the highest sideband amplitudes occur at lower frequencies and the signal offset magnitude is approximately-16 dB, indicating a significant extent of failure. Similarly for two broken bar magnitude is -11.5 dB, three broken bar magnitude is -5.7 dB, four broken bar magnitude is -6.6 dB, and for one short ring magnitude is -21.6 dB.

5 Laboratory Measurements

It has measured the same rotor faults analyzed by Maxwell 2D FEM electromagnetic rotor model for laboratory measurements. The main objective is this research to compare simulated analysis with practical measurements.

The following equipment is needed for practical measurements to determine the rotor faults as-.

1. *Disassembled Rotor set by frame, with PM, set under the rotor for increasing excitation.*
2. *RMF Coil for sensing, with around 2000 turns.*
3. *Permanent Magnet (PM) set in front of the rotor.*
4. *Oscilloscope (TiePie) for getting the data from the sensors.*
5. *Stepper Motor with Speed control for rotating the rotor.*
6. *A computer for waveforms from the oscilloscope.*

The measurement setup is shown in Figure 5.1.

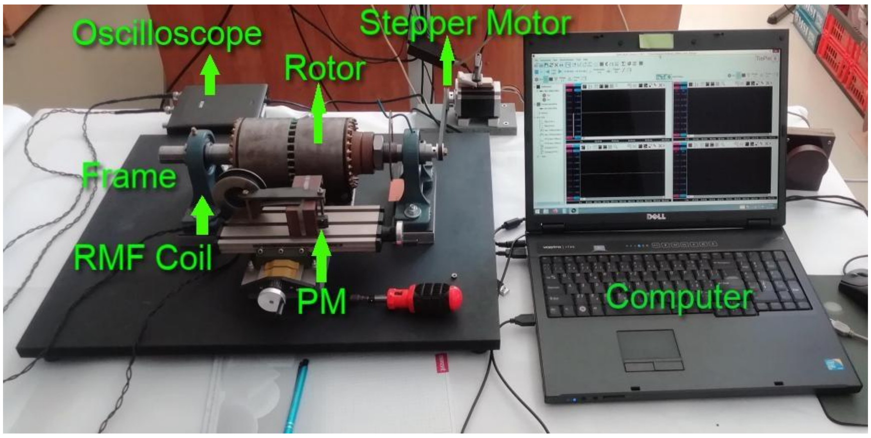


Figure 5. 1: Measurement Setup in the Laboratory

The broken rotor bar is made by the unscrewing from the end rings of the rotor in the laboratory is shown in figure 5.2.

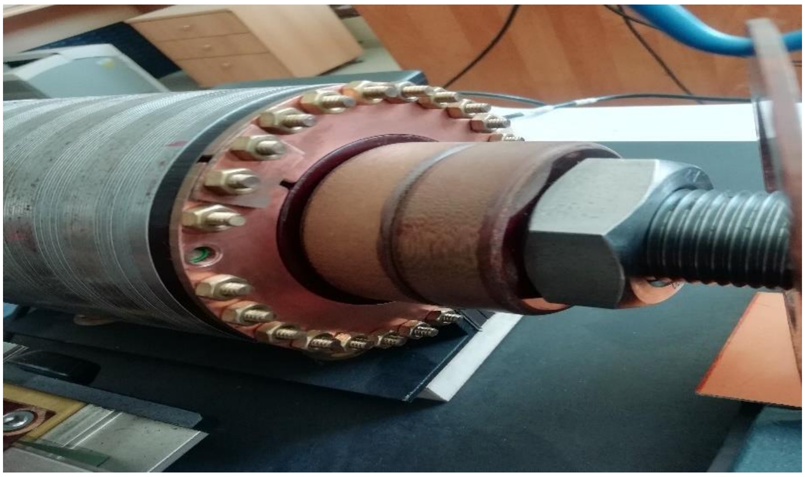


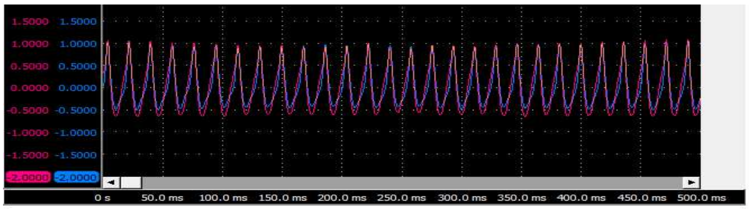
Figure 5. 2: Broken Rotor in Lab

5.1 Experimental Results by FFT Analysis

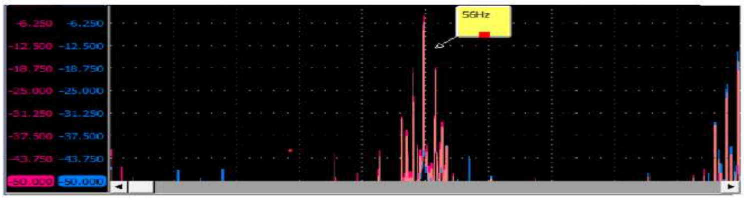
The obtained results at the laboratory, however recorded with multi-channel TiePie oscilloscope version 1.44 by FFT analysis. The fundamental harmonic f_s= 56Hz, is set by the speed control of the rotor.

5.1.1 Healthy Rotor

Measured waveform of the induced voltage from the RMF coil is shown in Figure 5.2. The healthy rotor has a regular induced voltage waveform without deviations. Harmonics with shift frequency Δf= 4Hz are also visible in the FFT spectrum.



(a) Time Domain



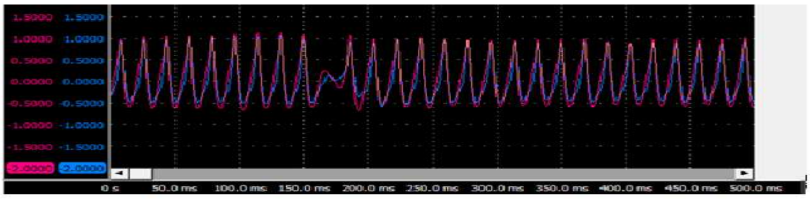
(b) FFT

Figure 5. 3: FFT Spectrum of Healthy Rotor

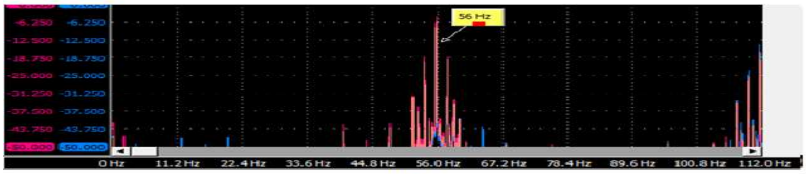
5.1.2 Faulty Rotor Bar

In addition, the bar faults also show an increased amplitude and delayed relatively long transient. Around the fundamental harmonic is same as healthy rotor, including their multiples, there is a dramatic increase in sidebands separated by Δf= 2.1Hz.

The FFT analysis of RMF induced voltage for one, two, three and four BRBs are shown that in Figure 5.4, 5.5, 5.6 and 5.7 respectively. The FFT spectrum for short ring shows in Figure 5.8.

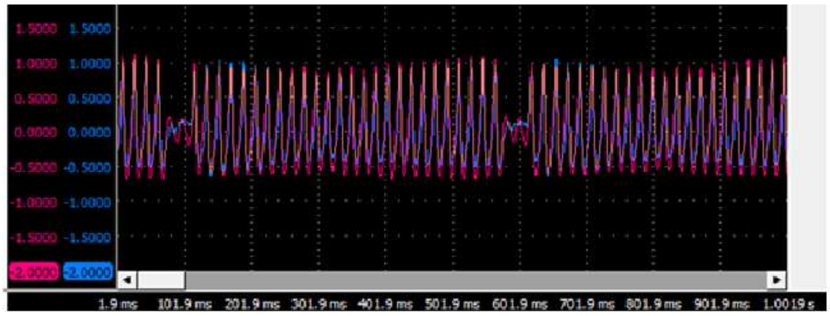


(a) Time Domain

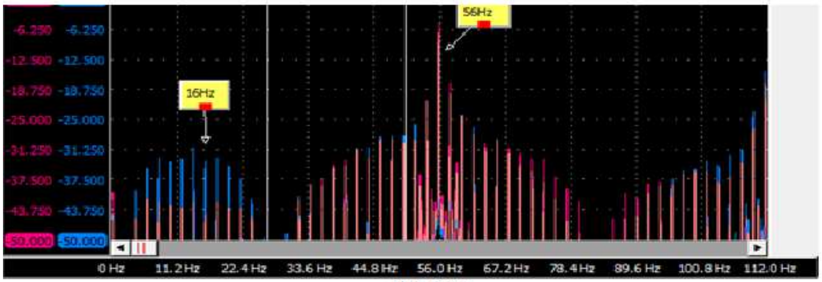


(b) FFT

Figure 5. 4: FFT Spectrum of One Broken Bar

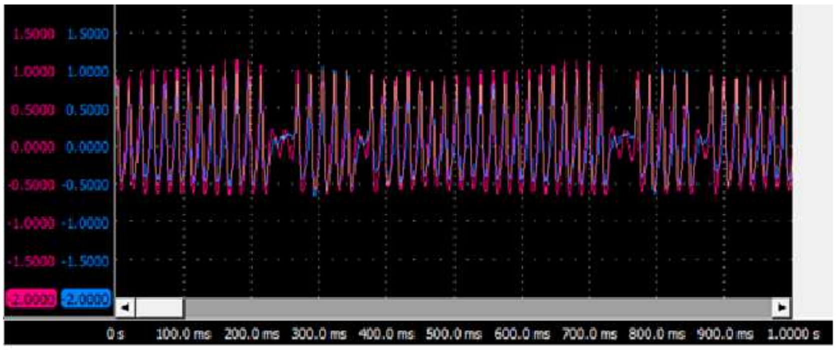


(a) Time Domain

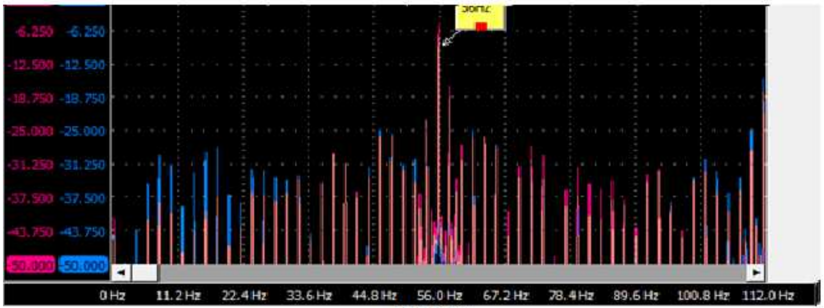


(b) FFT

Figure 5. 5: FFT Spectrum of Two Broken Bar

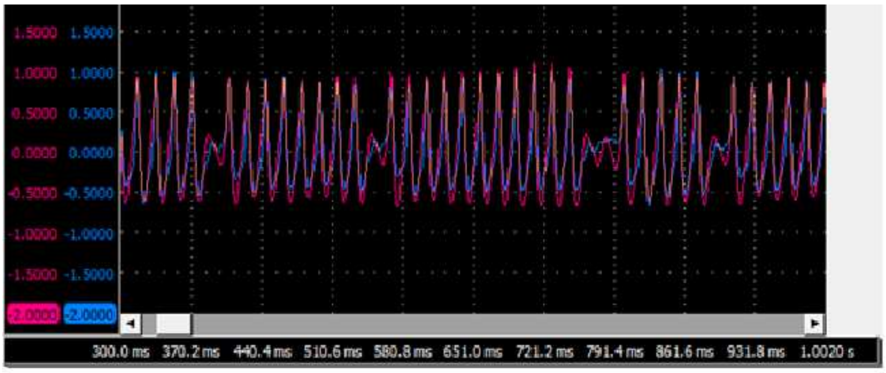


(a) Time Domain

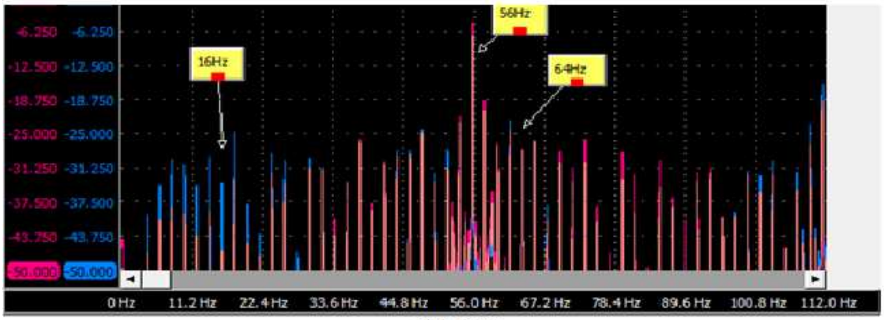


(b) FFT

Figure 5. 6: FFT Spectrum of Three Broken Bar

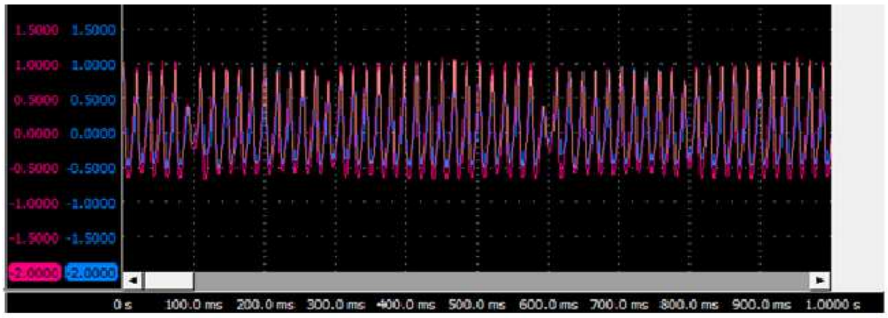


(a) Time Domain

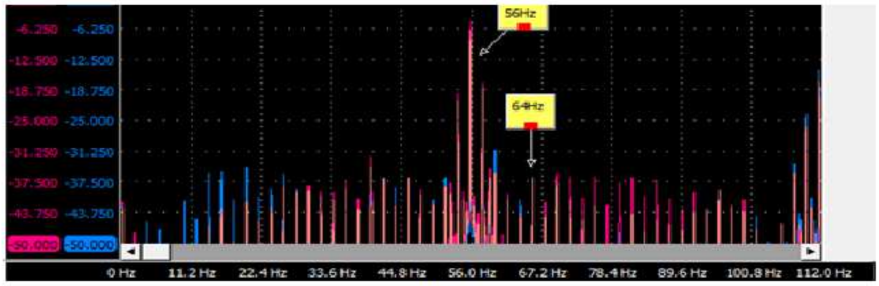


(b) FFT

Figure 5. 7: FFT Spectrum of Four Broken Bar



(a) Time Domain



(b) FFT

Figure 5. 8: FFT Spectrum of Short Ring

The output of oscilloscope is obtained from the 2 channels. The highest sideband amplitudes occur at lower frequencies and the signal offset magnitude is approximately-20 dB for all fault scenarios.

5.2 Evaluation

This study is performed in both simulations and practical measurements. There are few variations in both cases. Maxwell 2D model analysis is basically used for the analysis before manufacturing and the practical measurements used after manufacturing. The accuracy of the Maxwell 2D model analysis electromagnetic FEM model in predicting rotor faults. Compare the simulated results with known fault conditions to assess the model's ability to detect and characterize different types of faults accurately. The model can accurately capture and quantify these parameters, allowing for effective fault diagnosis. The complexity of Maxwell 2D model mainly complexity of the model, meshing requirements, and the computational power needed for accurate results.

The main facts of comparing the simulation and practical measurements as,

- *The main fact is the difference between the rotor bar shapes. In the 2D electromagnetic model, the rotor bar was circular shape and in lab the bar shape was full rod cylindrical.*
- *The faults made in laboratory to disconnect the rotor bars from end rings of the rotor.*
- *Permanent Magnet materials are different in both cases.*
- *Consider the simple 2 pole shape in the laboratory.*
- *In simulation used one PM for field excitation on the other hand in laboratory there were two permanent magnets used. The increased the filed excitation.*
- *In practical analysis, the RMF coils have the crucial role to detect the signal. The better sense coil can provide the more precise results.*

However, the main analysis is based on the FFT spectrum, so that there are no major changes in the two different categories. The significance of FFT analysis lies in its ability to reveal distinct fault signatures in the frequency spectrum. Rotor faults introduce unique frequency components due to the uneven distribution of magnetic forces or mechanical imbalances. By analyzing the amplitudes and positions of these fault-related frequencies, FFT analysis can accurately diagnose rotor faults and differentiate them from other sources of vibration or electrical disturbances by the only frequency spectrums. So that, it can be easier to detect the faults in the rotor of IM. For ability to improve diagnostic accuracy, enable condition monitoring, and ultimately enhance the reliability and performance of asynchronous machines.

6 Conclusion

Offline fault diagnostic methods, complementing the 2D electromagnetic model, enable the analysis of measured signals, such as vibration, current, or magnetic field, to identify fault-related frequencies and their harmonics. By employing techniques like FFT analysis, wavelet transforms, or envelope analysis, fault signatures can be extracted from the signals, facilitating the detection and characterization of rotor faults.

The combination of a 2D electromagnetic rotor faults model and offline fault diagnostic methods offers a comprehensive and accurate approach to identify and diagnose rotor faults. This approach enhances the reliability and efficiency of electrical machines by enabling early fault detection, proactive maintenance, and prevention of catastrophic failures.

Further advancements in 2D electromagnetic modeling techniques and offline fault diagnostic methods hold promise for improving accuracy, sensitivity, and speed of fault detection. This ongoing research and development will continue to contribute to the optimization of maintenance strategies, extended machine lifespan, and improved performance of electrical machines in diverse industrial applications.

The results from both cases, the FFT analysis enables the comparison of measured spectra with established fault databases or theoretical models, facilitating fault classification and severity assessment. This information guides maintenance decisions and enables timely interventions to prevent further deterioration or catastrophic failures.

Furthermore, FFT analysis allows for the identification of additional features, such as sidebands, harmonics, or amplitude modulation, which can provide further diagnostic information and contribute to a comprehensive understanding of rotor faults. In this thesis, the measured data is done by FFT analysis.

In the final part of this study, the analyses FFT spectrum for the 2D model and practical measurements have been compared with this study.

In the laboratory the measurements are faster than the simulation. It means that the technique has significance for measuring the rotor faults. The broken rotor bar detections took 160 seconds to record the RMF induced voltage.

However, as the detection depends on the sensing RMF coil, in future it can for the improvement of sensing coil.

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