



Fault Analysis in Inverter-Fed and Line-Fed Induction Motors: Investigating Increased Bearing Friction and Rotor Eccentricity Using Finite Element Method

Mohammad Reza Yousefi ^{1,2*}, Iman Poorqasemi ¹, Ehsan Poorqasemi ¹, Amin Dehghani³

¹Department of Electrical Engineering, Na.C., Islamic Azad University, Najafabad, Iran

²Digital Processing and Machine Vision Research Center, Na.C., Islamic Azad University, Najafabad, Iran

³Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran

mr_yousefi@iaui.ac.ir, iman.pn1991@gmail.com, ehsanpoorqasemi@gmail.com, dehghani@ut.ac.ir

Abstract

In this paper, it is proposed that diagnosing faults in induction motors is a necessary process in the industry to improve the reliability of these machines. The analysis of bearing faults can be categorized by their effects and the signs that the machine manifests, such as increased friction, which can lead to negative torque, and rotor eccentricity, which can cause fluctuations in the air gap and potentially result in serious issues for the machine. This study investigates the electromagnetic field of an induction motor under two types of faults: increased friction and rotor eccentricity. The motor is supplied by both a three-phase voltage source from the main line and a three-phase voltage source from a PWM inverter in open loop configuration, using the finite element method (FEM). Key electromagnetic field parameters, including flux line distribution, flux density distribution, and radial air gap flux density, are analyzed. The analysis of the electromagnetic characteristics of the open-loop voltage source inverter-fed induction motor is conducted for both healthy and static eccentricity fault conditions, utilizing finite element analysis. The importance of electromagnetic field analysis lies in its ability to provide data regarding the positions of the stator and rotor, as well as the mechanical parameters of the induction motor. Consequently, monitoring the magnetic fields in the air gap and the current is often employed for diagnosing faults in induction motors. Electromagnetic field parameters such as speed, current, and flux distribution within the machine and the air gap are analyzed for both healthy and faulty motors with the assistance of ANSYS Maxwell Finite Element Analysis.

Keywords: Motor bearing failure, Rotor failures, Failure of induction motors, Bearing fault diagnosis, Motor bearing analysis, Bearing fault analysis

Article history: Received 2025/09/16; Revised 2025/11/09; Accepted 2025/11/20, Article Type: Research paper

© 2025 IAUCTB-IJSEE Science. All rights reserved,

<https://doi.org/10.82234/IJSEE.2025.1218194>

1. Introduction

Recently, the importance of monitoring the condition of electric machines and inverters has been increasing, as it helps prevent unexpected shutdowns. This method improves operational efficiency and reduces the capital costs associated with replacing and repairing electric machines. Asynchronous machines play a significant role in the industry due to their power, robust structure, and high maneuverability, making them very suitable in terms of working conditions, operational costs, and maintenance expenses. These features make induction motors superior to other types of motors, leading to their use as primary drives for critical applications, with approximately 85% of rotating machines in industries

being induction machines. Consequently, the timely and accurate diagnosis of faults in these machines is of great importance, as it helps prevent further damage. Induction motors are classified based on their power supply into two types: inverter-fed induction motors for variable speed applications and line-fed induction motors for constant speed applications [1].

Typically, 80% of mechanical faults occurring in induction machines lead to misalignment [2]. There are three types of misalignment: static, dynamic, and combined. In static misalignment, the rotor axis is displaced from the stator axis, causing the rotor to rotate around its own axis. Dynamic misalignment occurs when the rotor and stator axes are aligned, but

the rotor hub is not co-axial with the rotor axis. Combined misalignment happens when both static and dynamic misalignments exist in a machine [3].

The root causes of misalignment faults include frequent increases or decreases in load, manufacturing defects, oval-shaped stator cores, and mechanical resonance. Misalignment in electric machines leads to uneven air gap distances. If misalignment is not detected early, it will affect the motor's performance and ultimately damage the stator core, windings, and rotor body. Mechanical faults occur due to the failure of mechanical components in the motor, covering approximately 50% of the total faults in induction motors. Among these, misalignment is the most critical and severe fault. The analysis and diagnosis of air gap misalignment are obtained using stator current spectrum analysis [2].

The effects of misalignment on the stator and rotor core plates in the windings manifest as vibrations. One popular method for detecting misalignment faults is Motor Current Signature Analysis (MCSA). In practice, misalignment faults change with the motor's axis coordinates, leading to misalignment. Changes in the axes are caused by improper bearing positioning, unbalanced rotors, scratched bearing surfaces, mechanical vibrations at rated speed, and mechanical load asymmetry, which can lead to faults, sometimes occurring simultaneously [3].

Even under technically excellent conditions, a small percentage of misalignment may exist within tolerable limits. Significant changes in static misalignment are due to the negligible air gap length during static conditions, which depends on the magnitude and amount of deviation created. An abnormal weakness is similarly caused by an inappropriate area of the stator and rotor during assembly or by an oval-shaped stator [4]. The creation of an air gap is known to increase the quality of the electromagnetic field, recognized as uneven magnetic pull. Various reasons for misalignment faults include: bent shafts, bearing wear, misalignment, and mechanical vibrations. In reality, a wide range of unpredictable, static, dynamic, and combined defects occur, which not only affect work quality but also lead to unpredictable failures [5]. To accurately diagnose defects, the best and most precise conditions must be applied in measurements [6].

The finite element method can be used to analyze the electromagnetic components of induction motors under static misalignment fault conditions compared to healthy motor conditions. Utilizing the finite element method to analyze electromagnetic parameters under both healthy and faulty conditions is an optimal approach. The finite element method provides more accurate information during fault conditions with a demonstrative technique that leverages direct features. The finite element method

includes nonlinear components such as magnetic saturation, real properties of magnetic materials, windings placed in actual slots, and more [7-11].

Bearings are crucial components in machines that are subject to significant wear and tear. The quality of bearings deteriorates over time, increasing the friction of the device, which may lead to fluctuations in torque and speed. Generally, sliding bearings and ball bearings are widely used in electric machines, consisting of an inner ring, outer ring, ball raceway, and ball retainers. If prolonged pressure is applied to the bearings, they may be subjected to wear and premature failure. Poor lubrication, contamination, erosion, and pitting can lead to bearing failure and faults in induction motors, especially in inverter-fed induction motors. When the inverter powers the motor, the rapid switching of semiconductor switches (high switching frequency) in the inverter generates harmonic current components, shaft voltage, and current within the bearing loop in the induction motor, which may damage the machine [1]. Induction motors are the most commonly used electric motors in the industry, with nearly two-thirds of the faults occurring in these motors related to bearing failures [2].

Therefore, timely identification and diagnosis of bearing faults can prevent the failure of other components in electric motors and avoid costly repairs. Accurate and realistic simulations can help identify the causes of faults and prevent their occurrence, and timely detection can help mitigate further losses. In this research, we will examine the combined faults of increased friction and rotor misalignment in a single simulation. The simulation will be made as realistic as possible using Ansys Maxwell software, and efforts will be made to enhance the accuracy of the simulation by modifying the mesh during the implementation of the finite element method with Ansys Maxwell, aiming for a more realistic and comprehensive simulation.

2. Theoretical Foundations

In this research, in order to bring the simulation closer to reality, bearing faults are divided into two categories: increased bearing friction and rotor misalignment due to bearing failure. In the simulation of faults caused by increased bearing friction, the finite element method (FEM) will be used to analyze the electromagnetic fields of an induction motor with bearing faults, which is powered by a three-phase voltage source inverter using Pulse Width Modulation (PWM) and operates in an open-loop control system. Electromagnetic field parameters such as flux line distribution, flux density distribution, and radial air gap flux density will also be analyzed. The presence of bearing faults will be detected from the Fast Fourier Transform (FFT) spectrum related to the radial air gap flux density [10,11].

In the simulation of rotor misalignment, the finite element method will be employed to analyze the

characteristics of the electromagnetic fields, such as speed, current, and flux distribution (both on the motor and in the air gap) under healthy conditions and static misalignment fault conditions of the same induction motor. The importance of electromagnetic field analysis lies in the information it provides regarding the positions of the stator, rotor, and mechanical parameters of the induction motor. This is why monitoring the magnetic field in the air gap and the electric current of the induction motor is often conducted to investigate bearing faults.[2,3]

A) Bearing Friction Coefficient:

Ball bearings and roller bearings are widely used in mechanical machines with rotating components due to their significantly low friction compared to plain bearings and bushings. The lower friction and smooth operation of ball and roller bearings reduce the need for a very powerful motor to generate rotational motion, and their reduced wear increases the lifespan of machine components. However, even ball bearings and roller bearings, despite being labeled as anti-friction or anti-wear, have a small friction coefficient due to the surface contact between the rollers and balls, especially at high speeds. This level of friction is influenced by several factors, including the surface finish of the balls and other bearing components (primary factor), the type of ball, its shape and diameter (secondary factor), the material used in the production of the ball and roller bearings (tertiary factor), and, of course, the technology employed in the manufacturing of the ball and roller bearings, which depends on the brand of the manufacturer (fourth priority). The friction force generated by ball bearings and roller bearings, which acts as a limiting factor in their operational efficiency, can be calculated according to the following equation:

$$F = \mu \cdot P \quad (1)$$

In this equation, **F** represents the friction force, **P** is the vertical component of the load applied to the ball and roller bearings, and **μ** is the friction coefficient.

B) Rotor Misalignment:

One of the faults that may occur in electric machines is the misalignment between the rotor and stator axes. Misalignment leads to an uneven air gap between the stator and rotor, which can be categorized into static, dynamic, and a combination of both, referred to as mixed misalignment. In static misalignment, the rotor's rotational axis aligns with the symmetrical axis but is displaced from the symmetrical axis of the stator. In this case, the air gap distribution around the rotor is not uniform but varies over time. In dynamic misalignment, the symmetrical axis of the stator aligns with the rotor's rotational axis, but the symmetrical axis of the rotor is displaced. The air gap distribution in this case is a non-uniform time-

varying variable around the rotor. Static and dynamic misalignments tend to coexist, and in fact, combined misalignment should be considered. In this scenario, the center of the rotor, the center of the stator, and the center of rotation are displaced with respect to each other. Figure 1 illustrates the cross-sections of an induction motor with various types of misalignment.[6,8]

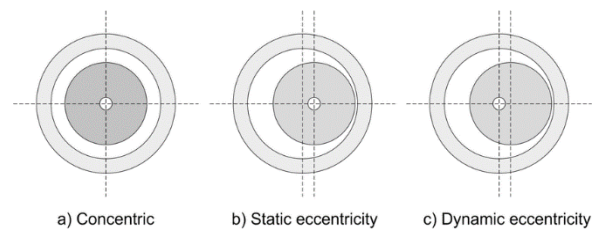


Fig. 1. Types of Misalignment. [3]

Fault detection systems are used as tools for maintaining and protecting costly systems against failures. These systems gather necessary information from the system or process and determine the quality of operations. If this status matches predefined fault conditions, the corresponding fault is indicated. The main advantage of fault detection systems is that by analyzing changes in specific parameters, they can predict the likelihood of damage and even determine the time of the fault and the reason for its occurrence. [11,12]

Mixed misalignment in an induction motor is caused by a bearing whose inner diameter, which surrounds the shaft, is slightly larger than the shaft diameter, while its outer diameter, which fits into a specific housing on the motor shaft, is smaller than the inner diameter specified in the housing. If the main bearing of the motor is changed, a gap will exist between the shaft and the inner surface of the bearing, as well as between the outer surface and the bearing housing on the body. These two gaps can be filled with two appropriately sized rings. If these rings are unconventional, a combined misalignment will occur in the motor. The smaller ring placed around the shaft creates dynamic misalignment, while if the fixed ring on the shaft rotates with it, the other ring placed on it creates static misalignment. In this case, the rotor's rotational axis aligns with its symmetrical axis but is displaced from the symmetrical axes of the stator. As a result, the air gap distribution around the rotor loses its uniformity, but the time remains constant. [6] If these two types of misalignment coexist, mixed misalignment is created. To determine static and dynamic misalignment, the ratio between the cylinder distances of the rings and the air gap length in the motor is defined by equations 2 and 3 [6].

$$\text{Static Axial Misalignment Degree} = \frac{(\text{Distance from the inner center of the ring to the roller axis})}{(\text{Length of the air gap in the motor})} \quad (2)$$

$$\text{Dynamic Axial Misalignment Degree} = \frac{(\text{Distance from the outer center of the ring to the roller axis})}{(\text{Length of the air gap in the motor})} \quad (3)$$

When the axes of the rotor and stator do not align with the rotational axis of the motor, the air gap becomes uneven. Approximately 80% of mechanical faults lead to misalignment between the stator and rotor [5]. This misalignment can occur during the manufacturing process and in research.

There are various types of misalignment, including static, dynamic, and mixed. When static misalignment occurs, the rotor's rotational axis aligns with its symmetrical axis, but it is displaced from the symmetrical axis of the stator. In this case, the air gap around the rotor loses its uniformity, but it remains constant over time. Figure 2 illustrates the cross-section of an induction motor with static misalignment [6].

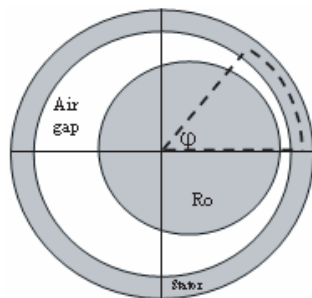


Fig. 2. Cross-section of an induction motor with static misalignment [3].

C) Finite Element Method

The finite element method is a numerical technique used to determine the electromagnetic parameters of electric machines based on their geometric dimensions and material properties. This method can provide accurate results from analyses. It estimates the distribution of the electromagnetic field and the nonlinear effects of the machine in parameters such as electromagnetic field distribution, leakage flux, electromagnetic torque, field intensity, and inductance. Faults can be detected through the evaluation and classification of machine parameters [6]. Therefore, the finite element method serves as a practical approach for fault detection in induction motors. Despite the importance of the finite element method, only a few of the methods discussed in research are based on this approach [5].

Fault detection in induction motors using the finite element method can be divided into three parts [4]:

- Fault detection approach based solely on the finite element method.
- Fault detection approach combining the finite element method with signal processing.
- Fault detection approach combining the finite element method with other advanced techniques.

In the first part, the finite element method is used independently for fault detection. The primary focus of

finite element analysis is on faults such as broken rotor bars (BRB), bearing faults, rotor misalignment, and stator faults. The second part mainly works on an approach that combines the finite element method with signal processing. Several methods for detecting broken rotor bars, bearing faults, stator faults, and rotor misalignment have been reviewed in the literature under this second approach. The third part presents a more advanced approach that combines the finite element method with machine learning, signal processing, or other advanced techniques. Very few works have been conducted based on the third method.

3. Method of Investigation

Considering that the output of the software consists of various graphs, we will analyze these graphs to assess the condition of the induction machine under different scenarios. The graphs we will examine include current-time, torque-time, speed-time, air gap flux density-time, and Fast Fourier Transform (FFT) graphs.

4. Simulation Results

The results obtained from this research are presented in several sections, including the results of current-time, torque-time, speed-time, air gap flux density over time, and the FFT graph related to the induction motor in healthy conditions, combined fault conditions, and maximum fault conditions. Finally, the results will be compared with those of other studies.

The simulation study was conducted on a three-phase induction motor rated at 380 volts, 1450 RPM, 50 Hz, and 7.5 kW. The overall structure of the induction motor model discussed is shown in the figure below. The details of the motor used are as follows:

Stator Data:

- Number of poles: 4
- Number of stator slots: 48
- Outer diameter of stator (mm): 210
- Inner diameter of stator (mm): 148
- Length of stator core (mm): 250
- Steel type: M19 24G
- Number of parallel branches: 2
- Number of conductors per slot: 30
- Number of wires per conductor: 2

Rotor Data:

- Number of rotor slots: 44
- Air gap (mm): 0.35
- Inner diameter of rotor (mm): 48
- Length of rotor (mm): 250
- Steel Type: M19 24G

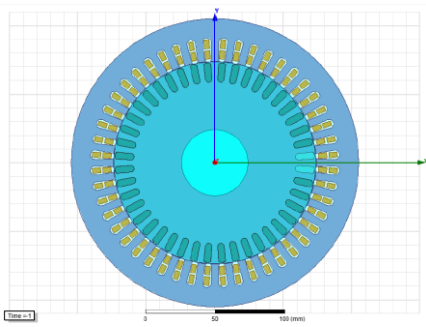


Fig. 3. Overall structure of the designed induction motor model.

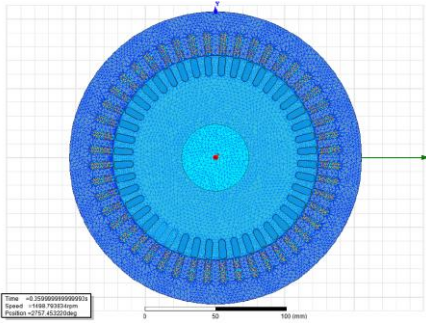


Fig. 4. Mesh generation of the problem domain.

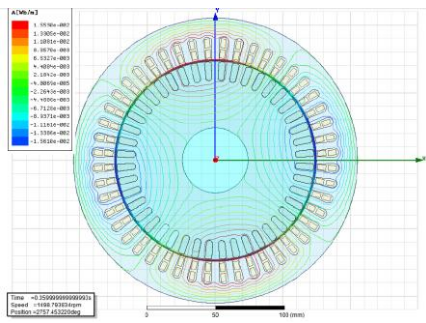


Fig. 5. Flux lines in the iron parts of the machine.

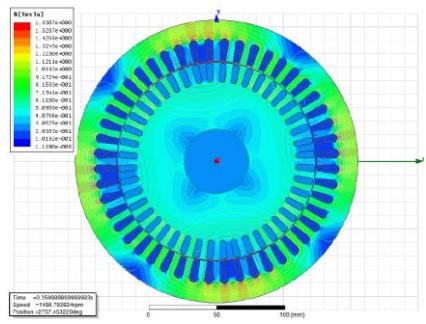


Fig. 6. Magnetic field density in the stator and healthy motor.

D) Simulation of Fault Conditions in an Induction Motor Powered by a Sine Wave Source

The various fault conditions can be observed in Table 1. The torque and speed of the induction motor powered by a sine wave source under all fault conditions are as follows. It is worth mentioning that the load is applied to the discussed induction motor at 400 milliseconds after the startup time. Combined fault (Condition 4) shows 40% higher torque ripple in Figures 7 and healthy motor stabilizes at 1450 RPM,

faulty conditions show 5-10% speed reduction in Figures 8. The torque and current of all three phases of the induction motor powered by a sine wave source in the first condition, with a bearing friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$ and a misalignment error of 0%, can be observed in Figures 9 and 10. The torque and current of all three phases of the induction motor powered by a sine wave source in the second condition, with a bearing friction coefficient of $0.3 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$ and a misalignment error of 0%, can be observed in Figures 11 and 12. The torque and current of all three phases of the induction motor powered by a sine wave source in the third condition, with a bearing friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$ and a misalignment error of 43%, can be observed in Figures 13 and 14. The torque and current of all three phases of the induction motor powered by a sine wave source in the fourth condition, with a bearing friction coefficient of $0.3 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$ and a misalignment error of 43%, can be observed in Figures 15 and 16.

Table.1.
Simulation Conditions

Condition	Friction ($\text{N}\cdot\text{m}\cdot\text{s}/\text{rad}$)	Misalignment	Fault Type
1	0.009 (Healthy)	0%	Baseline
2	0.3	0%	Increased Friction
3	0.009 (Healthy)	43%	Eccentricity Only
4	0.3	43%	Combined Fault

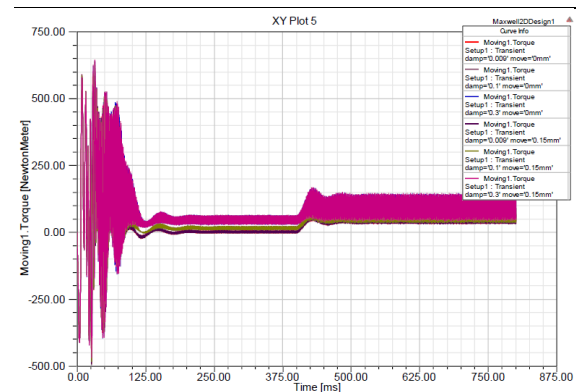


Fig. 7. Torque-time characteristics under all fault conditions

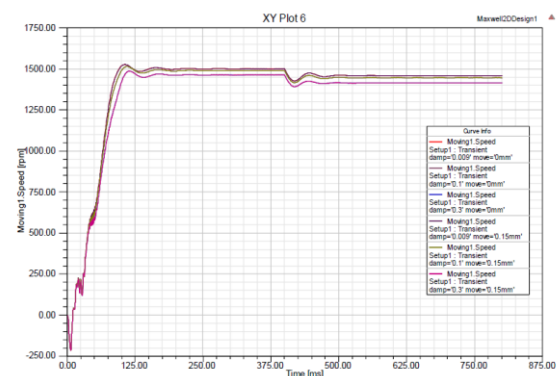


Fig. 8. Speed-time characteristics showing speed reduction under fault conditions

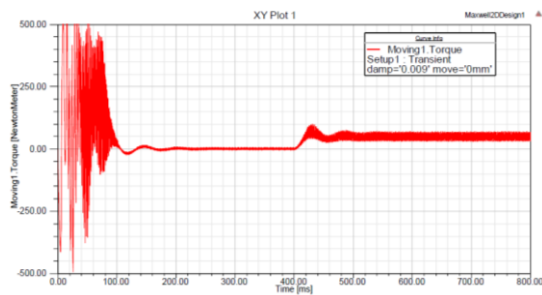


Fig. 9. Torque-time graph in the first condition.

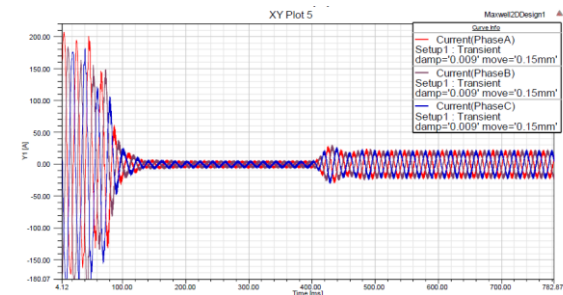


Fig. 14. Current-time graph in the third condition.

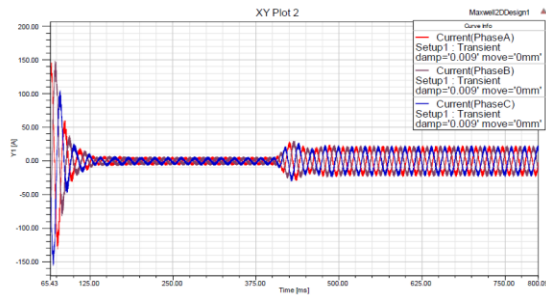


Fig. 10. Current-time graph in the first condition.

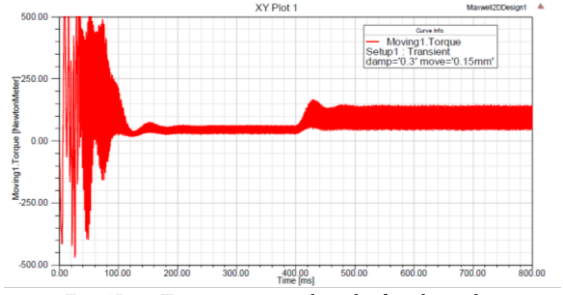


Fig. 15. Torque-time graph in the fourth condition.

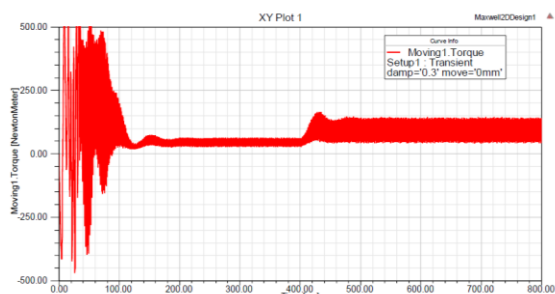


Fig. 11. Torque-time graph in the second condition.

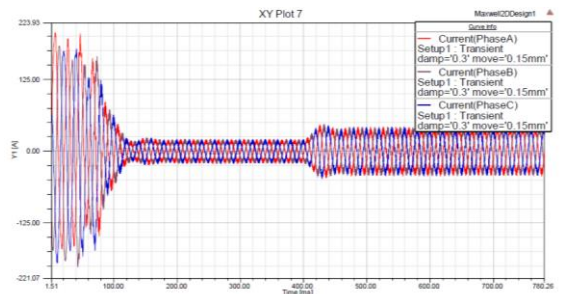


Fig. 16. Current-time graph in the fourth condition.

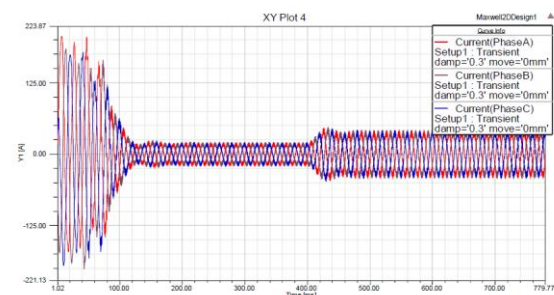


Fig. 12. Current-time graph in the second condition.

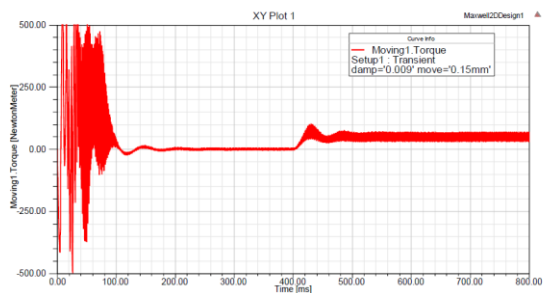


Fig. 13. Torque-time graph in the third condition.

E) Transient Analysis of the Induction Machine Powered by Line (Without Inverter):

The results of all fault conditions in the induction motor powered by a sine wave source are presented in the above figures. The induction motor is directly connected to a three-phase supply from the line. The machine is started without a load, and the nominal load is applied to the machine. The electromagnetic torque and line current of the machine are as mentioned above. For the healthy bearing conditions, the maximum phase current is 148 amperes. When an increase in the friction coefficient error is applied to the induction motor (considering healthy misalignment), in the second condition (friction coefficient of 0.3 N·m·s/rad), the maximum current increases to 208.7 amperes. In the next step, by applying a 43% misalignment error to the healthy motor (friction coefficient of 0.009 N·m·s/rad), the maximum current reaches 207.2 amperes, and in the fourth condition, with a 43% misalignment error applied to the faulty motor (friction coefficient of 0.3 N·m·s/rad), the maximum current becomes 210.4 amperes. The results of the maximum current are summarized in Table 2.

Table.2.
Maximum Current for All Different Simulation Conditions

Fault Condition	Maximum Current (Amperes)	Friction (Newton meter second per radian)	Misalignment
1	148	0/009Healthy	Healthy
2	208/7	0/3	Healthy
3	207/2	0/009Healthy	43%
4	210/4	0/3	43%

As can be seen in Table 2, in comparison, the maximum current in the first condition (considering healthy misalignment and a friction coefficient of 0.009 N·m·s/rad) and the second condition (considering healthy misalignment and a friction coefficient of 0.3 N·m·s/rad) shows an increase of about 40%. In comparison, the maximum current in the third condition (considering 43% misalignment and a friction coefficient of 0.009 N·m·s/rad) and the fourth condition (considering 43% misalignment and a friction coefficient of 0.3 N·m·s/rad) shows an increase of about 1.5%, indicating the significant impact of increased friction coefficient on the maximum current of the induction motor.

In comparison, the maximum current in the first condition (considering healthy misalignment and a friction coefficient of 0.009 N·m·s/rad) and the third condition (considering 43% misalignment and a friction coefficient of 0.009 N·m·s/rad), which represents the induction motor with misalignment error, also shows an increase of about 40% in maximum current, indicating the effect of misalignment on maximum current. Changes in phase current induce torque fluctuations, which increase ripple by up to 40% and reduce the average torque.

The sinusoidal distribution of air gap flux density for a healthy 4-pole induction machine at full load is shown in the figure below. As can be seen, apart from the jumps at the locations where the teeth pass and the slot opening, the point discontinuities are inherent to the numerical solution and meshing. As observed, the field along the arc is uniformly sinusoidal with equal amplitudes and is divided into four poles. The sinusoidal distribution of air gap flux density for a 4-pole induction machine with 43% misalignment and a friction coefficient of 0.3 N·m·s/rad at full load is shown in the figure below. In the case of rotor displacement from the center, both the number of point discontinuities has increased, and the maximum and minimum values of the field have changed. The FFT spectrum of the air gap flux density for both healthy and faulty machines is shown in Figures 19 and 20. From the FFT spectrum, it can be observed that the amplitude of the fundamental components decreases with an increase in friction and increases with an increase in misalignment. The amplitude of the harmonics at a distance of 100 millimeters, compared to the healthy conditions shown in Table 3, increases with an increase in friction and decreases with an

increase in misalignment. Additionally, the amplitude of the harmonics at a distance of 200 millimeters, compared to the healthy conditions shown in Table 3, increases. FFT spectra comparison showing harmonic amplitude changes in figure 19 and 20.

F) Transient Analysis of an Induction Motor Powered by an Inverter:

The inverter has been designed and implemented as shown in Figure 21. The induction machine powered through an inverter is considered under open-loop conditions with sinusoidal pulse width modulation and a switching frequency of 1 kHz.

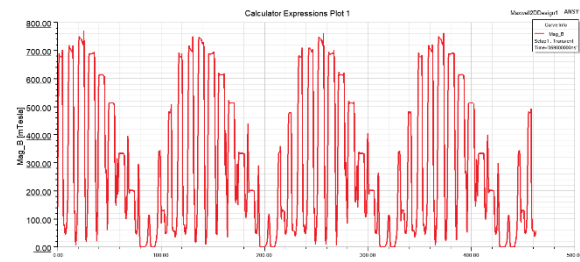


Fig. 17. Air Gap Flux Density of a Healthy Induction Machine Powered by a Sine Wave Source.

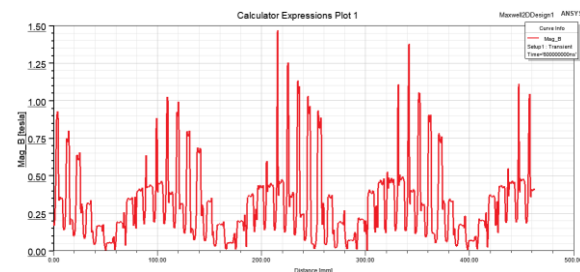


Fig. 18. Air Gap Flux Density of a Faulty Induction Machine Powered by a Sine Wave Source.

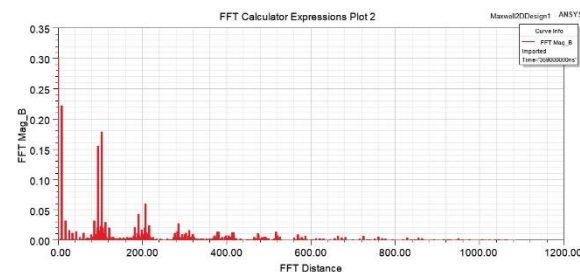


Fig. 19. FFT Spectrum of Air Gap Flux Density of a Healthy Induction Machine Powered by a Sine Wave Source.

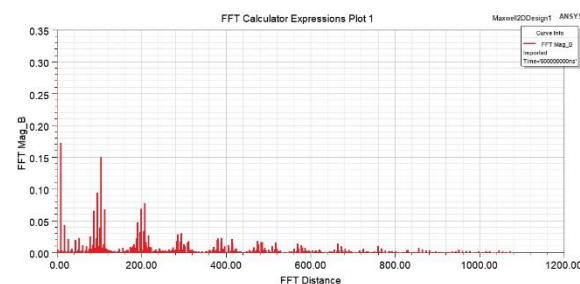


Fig. 20. FFT Spectrum of Air Gap Flux Density of a Faulty Induction Machine Powered by a Sine Wave Source.

Table.3.
FFT Spectrum Values in All Different Simulation Conditions

Fault Condition	200 Millimeter Component	100 Millimeter Component	Fundamental Component	Friction (Newton meter second per radian)	Misalignment
1	0/06	0/18	0/30	0/009)Healthy (	Healthy
2	0/08	0/21	0/28	0/3	Healthy
3	0/07	0/13	0/34	0/009)Healthy (	43%
4	0/08	0/15	0/31	0/3	43%

This results in distortion in the line voltage and line current due to the switching operation of semiconductor devices, leading to an increase in spatial harmonics in the air gap and noise in the machine.

The wide range of harmonic spectrum makes the Motor Current Signature Analysis (MCSA) technique insufficient for inverter-fed conditions. The following figures display the speed, magnetic torque, line current, and line voltage of the machine under healthy bearing conditions (considering healthy misalignment and a friction coefficient of 0.009 N·m·s/rad).

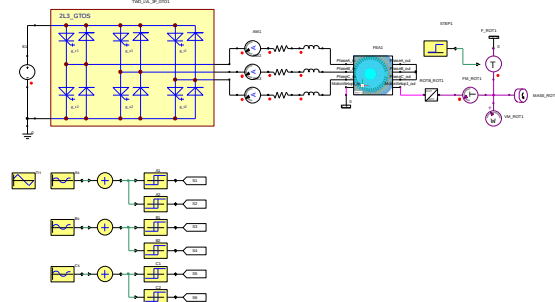


Fig. 21. Design Diagram of an Induction Motor Powered by an Inverter.

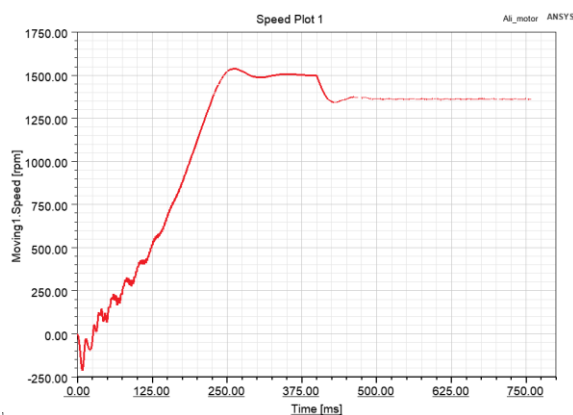


Fig. 22. Speed-Time Graph of a Healthy Induction Motor Powered by an Inverter.

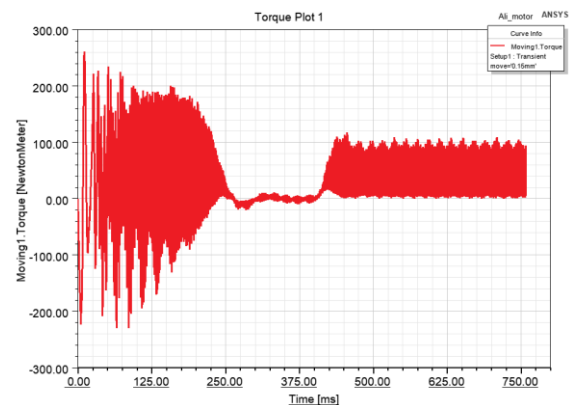


Fig. 23. Torque Graph of a Healthy Induction Motor Powered by an Inverter.

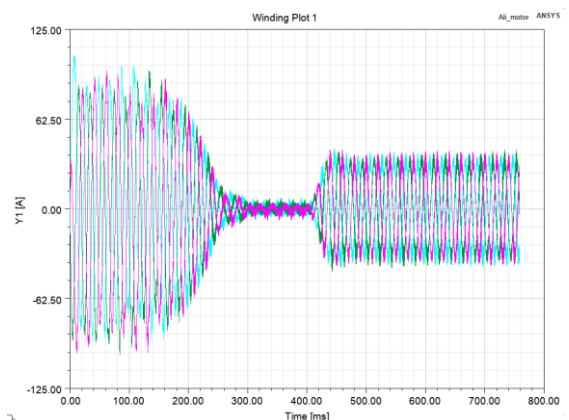


Fig. 24. Current-Time Graph of a Healthy Induction Motor Powered by an Inverter.

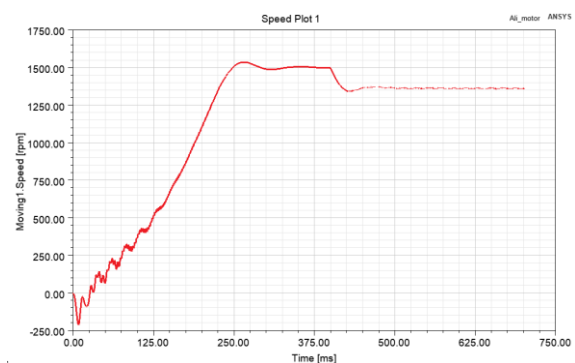


Fig. 25. Speed-Time Graph of a Faulty Induction Motor Powered by an Inverter.

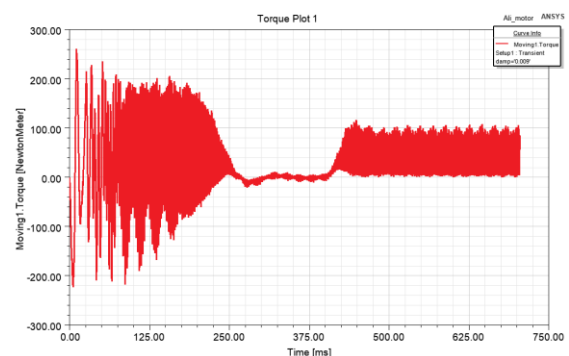


Fig. 26. Torque Graph of a Faulty Induction Motor Powered by an Inverter.

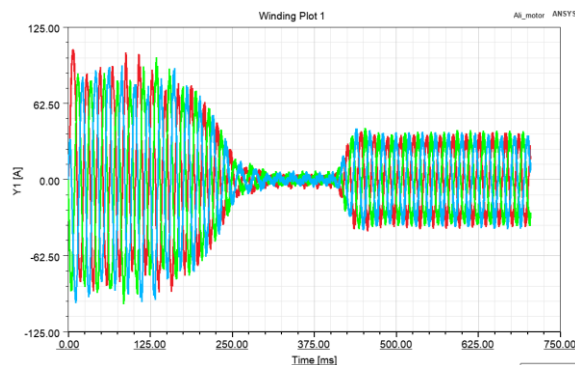


Fig. 27. Current-Time Graph of a Faulty Induction Motor Powered by an Inverter.

As shown in Figure 27, the increase in the friction coefficient of the bearings consequently raises the phase current peak, which leads to heating of the stator windings and, in addition, distortion. The line current results in fluctuations in the machine's torque and increased ripple under the worst bearing conditions. This leads to oscillations in the machine's speed and a reduction in the average shaft speed. The average speed of the healthy machine (considering healthy misalignment and a friction coefficient of 0.009 N·m·s/rad) has decreased from a steady-state speed of 1450 rpm to 1324 rpm, while the average speed of the faulty machine (considering 43% misalignment and a friction coefficient of 0.3 N·m·s/rad) has decreased from a steady-state speed of 1450 rpm to 1305 rpm, indicating a reduction in the average shaft speed. The increase in the severity of the fault results in an increase in distortion in the flux lines.

The sinusoidal distribution of the air gap flux density for the induction machine powered by an inverter and with 4 healthy poles at full load is shown in the figure below. As can be seen, apart from the jumps at the points of passage through the teeth and the slot opening, the point breaks are inherent to the numerical solution and meshing, as well as the PWM nature of the waveforms. As observed, the field is uniformly sinusoidal along the arc with equal amplitudes and is divided into four poles.

The sinusoidal distribution of the air gap flux density for a 4-pole induction machine powered by an inverter, with 43% misalignment and a friction coefficient of 0.3 N·m·s/rad at full load, is shown in the figure below. In the case of rotor misalignment, both the number of point jumps has increased and the maximum and minimum values of the field have changed.

The spatial FFT spectrum of the air gap flux density for both healthy and faulty induction machines powered by an inverter is shown in Figures 30 and 31. According to Table 4, it can be observed from the FFT spectrum that the amplitude of the fundamental components increases under faulty conditions, while the amplitude of the harmonics at a distance of 100 mm decreases compared to the healthy condition, and the

amplitude of the harmonics at a distance of 200 mm increases compared to the healthy condition.

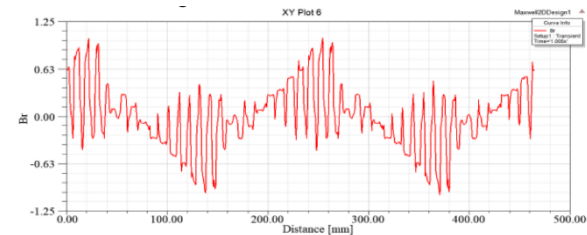


Fig. 28. Air Gap Flux Density of a Healthy Induction Machine Powered by an Inverter.

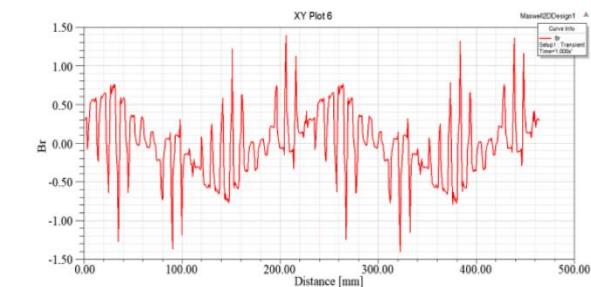


Fig. 29. Air Gap Flux Density of a Faulty Induction Machine Powered by an Inverter.

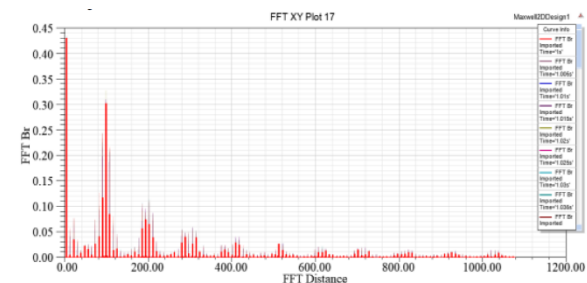


Fig. 30. FFT Spectrum of Air Gap Flux Density of a Healthy Induction Machine Powered by an Inverter.

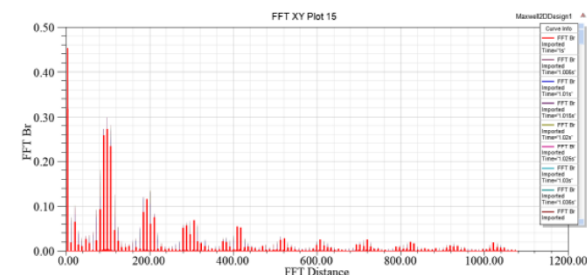


Fig. 31. FFT Spectrum of Air Gap Flux Density of a Faulty Induction Machine Powered by an Inverter.

Table.4.

FFT Spectrum Values in All Different Simulation Conditions.

200 Millimeter s	100 Millimeter s	Fundament Component	Friction (N·m·s/rad)	Misalignme nt	Fault Conditio n
Compone nt	Compone nt				
0/07	0/30	0/43	0/009	Healthy	1
0/11	0/27	0/45	0/3	43%	2

5. Conclusion

In this research, the electromagnetic analysis of induction motors powered by line supply and inverter supply under normal and abnormal bearing conditions was analyzed using the FEM method.

Wear and tear of the bearings is accompanied by an increase in the friction coefficient of the motor shaft in the FEM method. As wear and tear in the bearings increases, the current ripple increases, leading to torque ripple and a reduction in average speed.

The occurrence of misalignment errors in the induction motor also indicated that it is possible to detect faults in the motor shaft by analyzing the frequency spectrum of the stator current. In this study, a method based on the harmonic analysis of stator currents was proposed to detect misalignment faults in the squirrel-cage rotor. The misalignment fault applied in this research is of the equal type, meaning that the displacement in both bearings of the induction motor is equal, such that after the occurrence of the misalignment fault, the axes of the stator and rotor are parallel, and only displacement occurs in the rotor axis.

In the analysis of the induction motor powered by a sinusoidal source, as can be seen in Table 2, the maximum current in the first condition (considering healthy misalignment and a friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) compared to the third condition (considering healthy misalignment and a friction coefficient of $0.3 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) shows an increase of about 40%. Additionally, the maximum current in the fourth condition (considering 43% misalignment and a friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) compared to the sixth condition (considering 43% misalignment and a friction coefficient of $0.3 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) shows an increase of about 1.5%, indicating the significant impact of the increase in the friction coefficient on the maximum current of the induction motor.

The comparison of the maximum current in the first condition (considering healthy misalignment and a friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) and the fourth condition (considering 43% misalignment and a friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$), which indicates the induction motor with a misalignment fault, also shows an increase of about 40% in maximum current, demonstrating the effect of misalignment on maximum current. Changes in phase current induce torque fluctuations, which increase ripple by up to 40% and reduce average torque.

The spatial FFT spectrum of the air gap flux density for both healthy and faulty machines is shown in Figure 24. From the FFT spectrum, it can be observed that the amplitude of the fundamental components increases under faulty conditions, while the amplitude of the harmonics at a distance of 100 mm decreases compared to the healthy condition, as seen in Table 2. Conversely, the amplitude of the harmonics at a distance of 200 mm increases compared to the healthy condition, also as seen in Table 2.

In the analysis of the induction motor powered by an inverter, as shown in Figure 32, the increase in the friction coefficient of the bearings consequently raises the phase current peak, which leads to heating of the stator windings and, in addition, distortion. The line current results in fluctuations in the machine's torque and increased ripple under the worst bearing conditions. This leads to oscillations in the machine's speed and a reduction in the average shaft speed. The average speed of the healthy machine (considering healthy misalignment and a friction coefficient of $0.009 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) has decreased from a steady-state speed of 1450 rpm to 1324 rpm, while the average speed of the faulty machine (considering 43% misalignment and a friction coefficient of $0.3 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$) has decreased from a steady-state speed of 1450 rpm to 1305 rpm, indicating a reduction in the average shaft speed. The increase in the severity of the fault results in an increase in distortion in the flux lines.

The spatial FFT spectrum of the air gap flux density for both healthy and faulty induction machines powered by an inverter is shown in Figures 30 and 31. According to Table 4, it can be observed from the FFT spectrum that the amplitude of the fundamental components increases under faulty conditions, while the amplitude of the harmonics at a distance of 100 mm decreases compared to the healthy condition, and the amplitude of the harmonics at a distance of 200 mm increases compared to the healthy condition.

Overall, the FFT spectrum of the radial air gap flux density indicates an increase in the amplitude of the fundamental components, a decrease in the amplitude at a radial distance of 100 mm, and an increase in the amplitude at 200 mm.

References

- [1] Priya BH, Karthick R, Lokprakash B, Vasanth S, Praveen NK. Static Eccentricity Fault Analysis in Inverter Fed Induction Motor using Finite Element Method. In IOP Conference Series: Materials Science and Engineering 2020 Jun 1 (Vol. 872, No. 1, p. 012049). IOP Publishing
- [2] Vinothraj C, Kumar NP, Isha TB. Bearing fault analysis in induction motor drives using finite element method. International Journal of Engineering and Technology (UAE). 2018;7(3):30-4
- [3] Priya BH, Karthick R, Lokprakash B, Vasanth S, Praveen NK. Static Eccentricity Fault Analysis in Inverter Fed Induction Motor using Finite Element Method. In IOP Conference Series: Materials Science and Engineering 2020 Jun 1 (Vol. 872, No. 1, p. 012049). IOP Publishing
- [4] Ojaghi M, Mohammadi M. Modeling eccentricity faults with axial asymmetry in three-phase induction motors. In IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society 2016 Oct 23 (pp. 1524-1529). IEEE
- [5] Sobra J, Kavalir T, Krizek M, Skala B. Experimental verification of the finite element analysis of an induction machine with implemented static eccentricity fault. In 2018 18th International Conference on Mechatronics-Mechatronika (ME) 2018 Dec 5 (pp. 1-5). IEEE
- [6] Kumar P, Isha TB, Balakrishnan P. Radial electro-magnetic field analysis of induction motor under faulty condition using

- FEM. In 2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE) 2016 Jan 21 (pp. 1-6). IEEE
- [7] Yousefi, M. R., Jafari, R., & Moghaddam, H. A. (2013). A combined wavelet-based mesh-free method for solving the forward problem in electrical impedance tomography. *IEEE Transactions on Instrumentation and Measurement*, 62(10), 2629-2638.
 - [8] Yousefi, M. R., Jafari, R., & Moghaddam, H. A. (2014). Imposing boundary and interface conditions in multi-resolution wavelet Galerkin method for numerical solution of Helmholtz problems. *Computer Methods in Applied Mechanics and Engineering*, 276, 67-94.
 - [9] Yousefi, M. R., Jafari, R., & Abrishami Moghaddam, H. (2014). A combined wavelet based mesh free-finite element method for solving the forward problem in magnetic induction tomography. *Iranian Journal of Biomedical Engineering*, 8(1), 69-86.
 - [10] Yousefi, M., Jafari, R., & Abrishami Moghaddam, H. (2020). Employing dual frequency phase sensitive demodulation technique to improve the accuracy of voltage measurement in magnetic induction tomography and designing a laboratory prototype. *Journal of Control*, 14(3), 89-102.
 - [11] Yousefi, M. R., Smith, F., Hatefi, S., Abou-El-Hossein, K., & Kang, J. Z. (2020). Coupled Multi-Resolution WMF-FEM to Solve the Forward Problem in Magnetic Induction Tomography Technology.
 - [12] Praveen Kumar N, Vinothraj C and Isha T B 2018 Effect of wear and tear bearing fault in induction motor drives using FEM IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)1-6
 - [13] Faiz J, Ebrahimi BM, Akin B, Toliyat HA. Finite-element transient analysis of induction motors under mixed eccentricity fault. *IEEE transactions on magnetics*. 2017 Dec 18;44(1):66-74.
 - [14] Liang, H., Saber-Samandari, S., Yusof, M. Y. P. M., Esfahani, M. M., Shahgholi, M., Hekmatifar, M., ... & Toghraie, D. (2022). Investigation of the effect of Berkovich and Cube Corner indentations on the mechanical behavior of fused silica using molecular dynamics and finite element simulation. *Ceramics International*, 48(19), 28781-28789.