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Review of Fault Detection Methods in Three-Phase Induction Motors Employed Techniques

Jaafar Falih Hasan[1]*, Ahmed Raisan Hussein[1]

[1]*Department of Electrical Engineering, College of Engineering, University of Misan, Maysan, Iraq.*
[1]*Corresponding author E-mail: enghre.20241@uomisan.edu.iq*

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Abstract: In this article, we have examined the major causes of failure that occur within three-phase induction motors. The factors contributing to this loss of efficiency and increased downtime are both electrical (i.e. stator winding short circuits, broken rotor bars) and mechanical (i.e., bearing problems, misalignment). We have compared existing methods of detecting faults, including insulation resistance testing, current and vibration analysis, acoustic monitoring and thermal monitoring, magnetic flux analysis based upon their ability to give accurate results regarding costs associated with establishing accurate early detection of faults. The limitations of conventional methods for identifying electrical and mechanical faults have been identified within this study as well as an indication that utilizing intelligent systems (e.g., artificial intelligence and machine learning) can result in faster diagnosis of faults and better predictions for the maintenance of these motors. Finally, paper suggested using a hybrid approach to diagnostics by combining traditional techniques and intelligent approaches to enhance performance at detecting faults and improving the reliability of motors.

Keywords: Three phase Induction motor; Condition monitoring; Faults detection; Electrical faults; Mechanical faults.

1. Introduction

Modern industrial drive systems are primarily driven by three-phase induction motors. These motor types are very easy to construct, provide high power density, and can run continuously in harsh environments. In addition, three-phase induction motors are one of the most common types of motor used in the process and manufacturing industries, as well as in any energy-related application; therefore, the reliability with which three-phase induction motors operate will directly affect the reliability of the entire production system. [1], [2] Any decline in the performance of an induction motor will result in decreases in the efficiency of the production system, increased consumption of energy, and a reduction in the level of safety at which the production system operates[3]. Three-phase induction motors are subjected to thermal, electrical, and mechanical stresses; these stressors evolve over time. Insulation degradation, electromagnetic imbalance, rotor asymmetry, as well as mechanical mechanisms that degrade motor performance (such as deterioration of bearings and misalignment of shafts) produce subtle changes to the behavior of the induction motors long before complete failure. Although these early-stage faults can be difficult to identify by traditional inspection methods, they also create large changes in torque output, vibration characteristics, and the distribution of the electromagnetic field in the induction motors. Therefore, condition monitoring is an important part of a modern motor maintenance strategy. Traditional diagnostic methods use measurable forms of physical evidence (stator current, vibration signature, noise signature, temperature distribution, and magnetic flux density in the air gap) [4], [5]. The growing need for high-quality reliability from minimal/zero maintenance costs in industrial level systems has demonstrated the limitations of purely conventional diagnostics.

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In complex and challenging operating environments, the signatures of faults may cross over or be hidden until they reach a very advanced level; thus many threshold/rule-based diagnostic schemes will be greatly impacted by this challenge; therefore, exploring more advanced data-driven approaches that can capture as well as subtle patterns within the diagnostic signals is the driving force behind the exploration of intelligent systems. In this environment, intelligent systems provide a new dimension to the traditional condition-monitoring systems by providing advanced feature extraction, improving fault classification accuracy, and providing informed predictive maintenance decisions through the integration of artificial intelligence (AI) and machine learning (ML) technologies [6].The incorporation of these intelligent tools with traditional diagnostic principles enables a systematic pathway for developing more reliable, adaptive, and early fault detection systems for three-phase induction motors.

Root Causes of Faults in Three-Phase Induction Motors

Electrical, mechanical, environmental, and operational stresses that occur throughout a motor's service life are responsible for most faults occurring in a three-phase induction motor. Three-phase induction motors are designed to operate continuously and reliably[2]. The expected service life of a three-phase induction motor will end when the internal parts of the motor have degraded due to continuous use in extreme operational environments. Most of the time, an electrical, mechanical, environmental, and operational stressors may slowly degrade the inside of the motor without showing any signs of failure until the deterioration of the internal components of the motor reaches a substantial level and performance is significantly reduced.From a purely electrical point of view, one of the most significant mechanisms that cause faults to occur is that of insulation deterioration [3],[7]. Insulation deterioration in stator winnings is typically caused by temperature overload, voltage unbalance, harmonic distortion, moisture intrusion, and contamination. Any of these stresses can result in the insulation breaking down, which in turn can lead to inter-turn short circuits or phase-to-phase faults. Changes to the distribution of the electromagnetic field in the machine would result from electrical problems, which would then create localized areas of heating in the machine, higher losses, and torque instability.[5].Motor rotor faults are often caused by faulty manufacturing, thermal cycling, and mechanical fatigue. Rotor bar breaks and end-ring failures can create an unbalanced rotor current, generate electromagnetic torque pulses, and result in increased vibration levels which will continue the cycle of mechanical wear in a motor. Increased vibration levels and magnetic torque pulsations have also contributed to increased mechanical wear on the motor. Mechanical failures are one of the leading causes of an induction motor’s failure. Mechanical faults occur primarily due to bearing deterioration. Bearing failure can occur because of insufficient lubrication, excessive radial and/or axial loads on the bearings, improper alignment of the motor shaft, contamination of the bearing, and/or improper installation techniques. The initiation of a bearing defect will result in the creation of increased levels of friction and vibration, which will affect the health of other components within the induction motor, including the rotor and stator core [6],[7]. As a result of the misalignment of the rotor shaft and the eccentric position of the rotor, the air gap will not be uniform in its position resulting in unbalanced forces on the motor, which will cause rapid deterioration to the structure of the motor. Environmental and operational conditions indirectly influence the creation of faults within an induction motor due to the accelerated aging of electrical insulation and the accelerated mechanical wear of the motor. Elevated ambient temperature, insufficient ventilation, dust accumulation, and corrosion or chemical attack on the motor will hasten the aging of the motor’s electrical insulation and mechanical wear. In addition, frequent start/stop cycles, overload operation and variable load conditions on the motor will contribute to repetitive mechanical and thermal stress on the induction motor creating fatigue-related failures [8] . These same stressors not only shorten the life of the induction motor but also create difficulties for fault detection due to the inability to identify early fault signatures that occur when the induction motor is within the normal operating range of the motor[9] . The relationship that exists between the various causes of fault development illustrates that the complexity of diagnosing an induction motor failure at an early stage is difficult. Electrical and mechanical faults frequently co-occur and both influence one another [10].

3. Three phase induction motor and faults detection

Although induction motors are efficient, installation difficulties, environmental conditions, and duty cycles may cause the motor failure rate to increase faster than planned. Induction motors are susceptible to a range of problems due to these reasons, including stator faults, bearing issues, rotor defects, broken bar failures, and other types of fault [4], [9].
The types of faults that a three-phase motor experiences can be classified as follows in (Fig. 1).

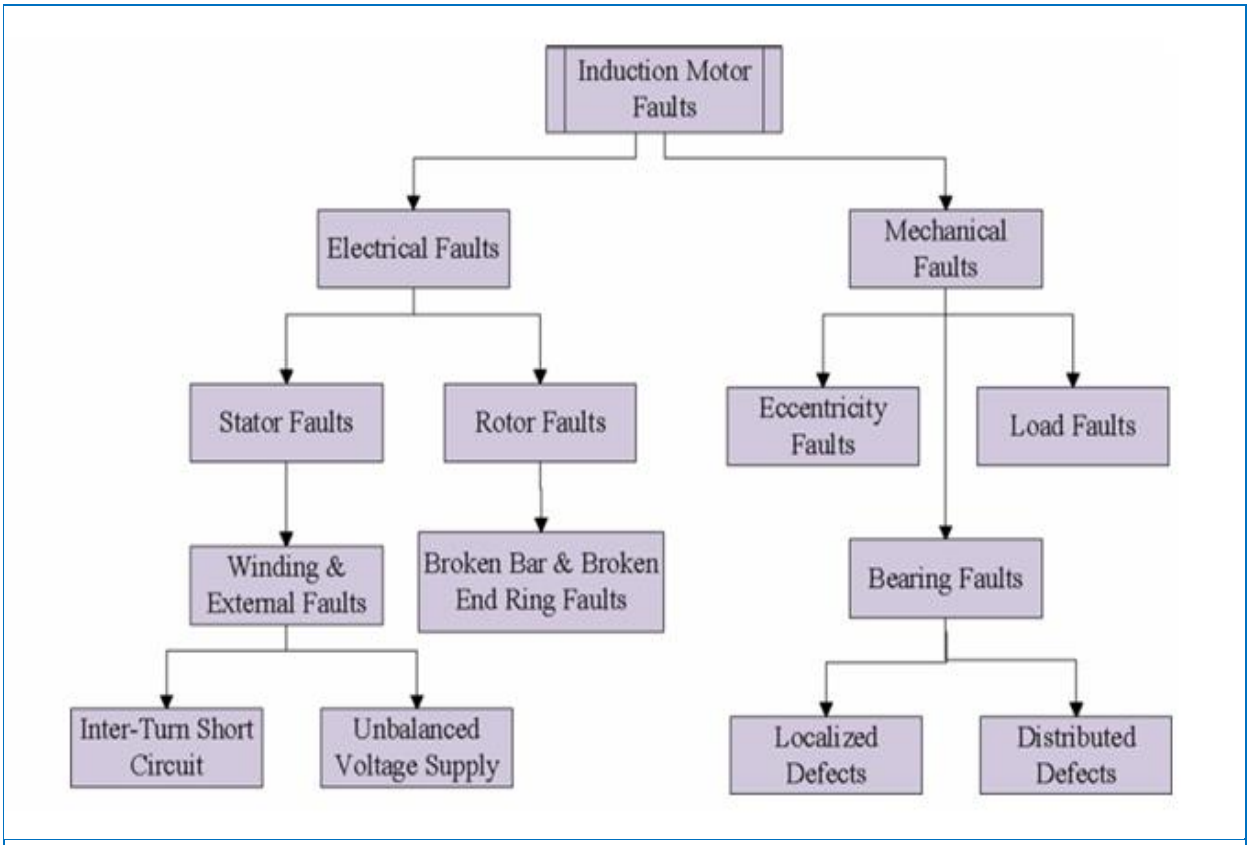


Fig. 1: Three phase Induction Motor fault types[6].

3.1 Electrical faults in three phase induction motor

It can be classified as :

3.1.1 Stator faults

One of the main elements that has a big impact on a three-phase induction motor's performance is the stator. Electrical problems, such as insulation failure or winding short circuits, are among the most frequent faults that can affect the stator. The motor may be harmed by these issues since they can result in higher current and excessive heat production [3],[7].Continuous shocks or vibrations can also cause mechanical problems in the stator, which can result in bearing failure or wear on metal surfaces. In addition, an imbalance in the electrical circuits could lead to irregular power flow. Overload situations or environmental elements like humidity or pollution are frequently the cause of these failures [10], [11]. A common problem with the stator three-phase induction motors is inter-turn short circuits. It happens when an inadvertent connection occurs between the stator's windings of the same phase or between phases, which lowers the electrical path's resistance. The damaged circuit gets an increase in current flow as a result. Excessive heat generation is one of the effects of this issue, which may destroy the insulation and other motor parts. Furthermore, this malfunction results in an unbalanced energy distribution, which

lowers the motor's efficiency and raises energy usage. It may seriously damage the motor if ignored, possibly resulting in a total motor failure [5], [11]. this types can be shown in fig.(2).

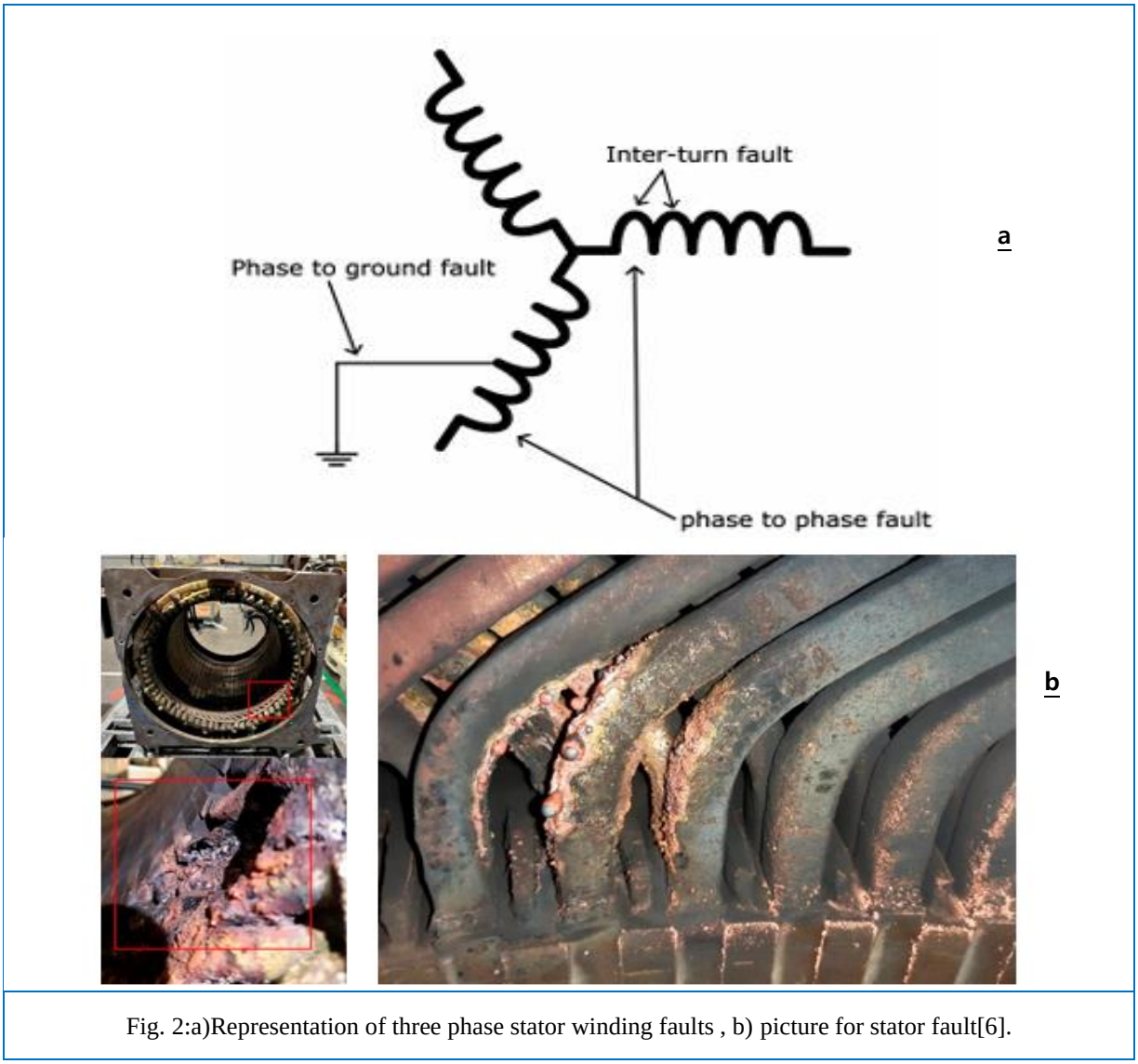


Fig. 2:a)Representation of three phase stator winding faults , b) picture for stator fault[6].

3.1.2 Unbalance voltage supply faults

When voltages applied to the phases of a three-phase motor have different phase angles or are of different voltage amplitudes, it is termed unbalanced voltage supply. An unbalanced voltage supply can cause decreased efficiency of the motor and increased temperature resulting in early failure of the motor's parts, such as windings and bearings [12, [13].

3.1.3 Rotor faults

The rotor is an important component which affects a three-phase induction motor's efficiency. Electrical failures, often broken bars or other damage to the insulation in the area between the bars, are one of the most common rotor failures. The root cause of this kind of problem may be a failure due to wear, or excessive heat produced from a combination of overload situations and/or adverse climatic conditions. Mechanical problems in the rotor can also happen as a result of continuous vibrations or imbalance such that the bearing will fail or malfunction [8]. Furthermore, issues with the electrical

connection between the bars and the laminations could occur, which would result in a lower motor efficiency and higher energy usage. These issues cause the electrical system to be under more stress, which progressively impairs the motor's performance [5], [14].the broken rotor bar onsite can be shown in Fig.(3).

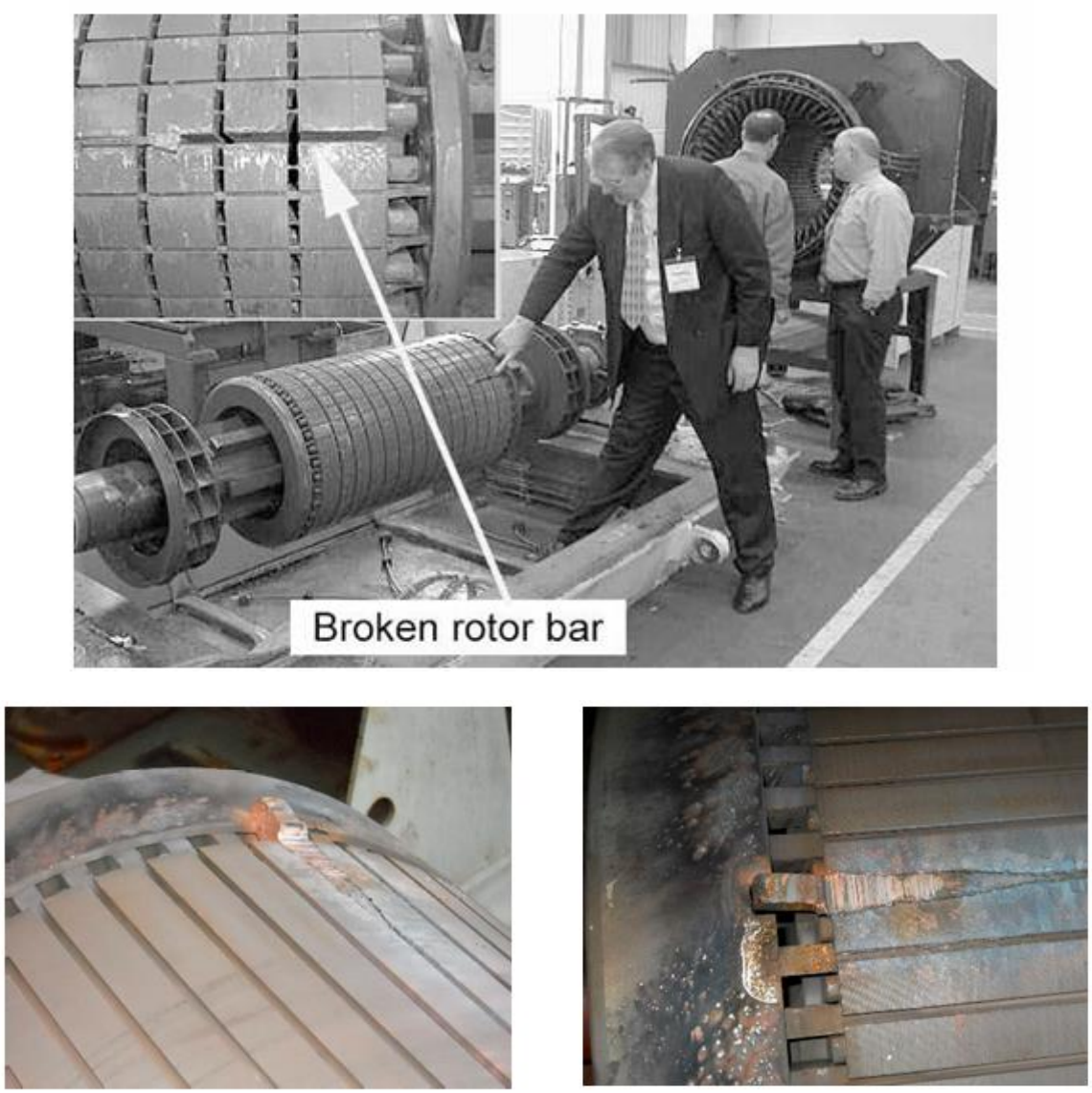


Fig. 3: onsite picture for broken rotor bar fault [10], [11].

3.2 machincal faults in three phase induction motor

It can be classified as:

3.2.1 Bearing faults

The bearing is one of the primary components of the three-phase induction motor to allow the rotor to rotate within the stator of the motor. The bearing is necessary to keep the performance of the motor as best as possible and reduce damage from friction between moving and static components. The bearing will have a number of issues over time due to frequent use, overload, or insufficient lubrication. If the bearing fails, the performance and noise of the motor may be affected, creating potential issues with vibration [8], [9]. to recognize the main part of bearing practically show fig. (4) and fig.(5).

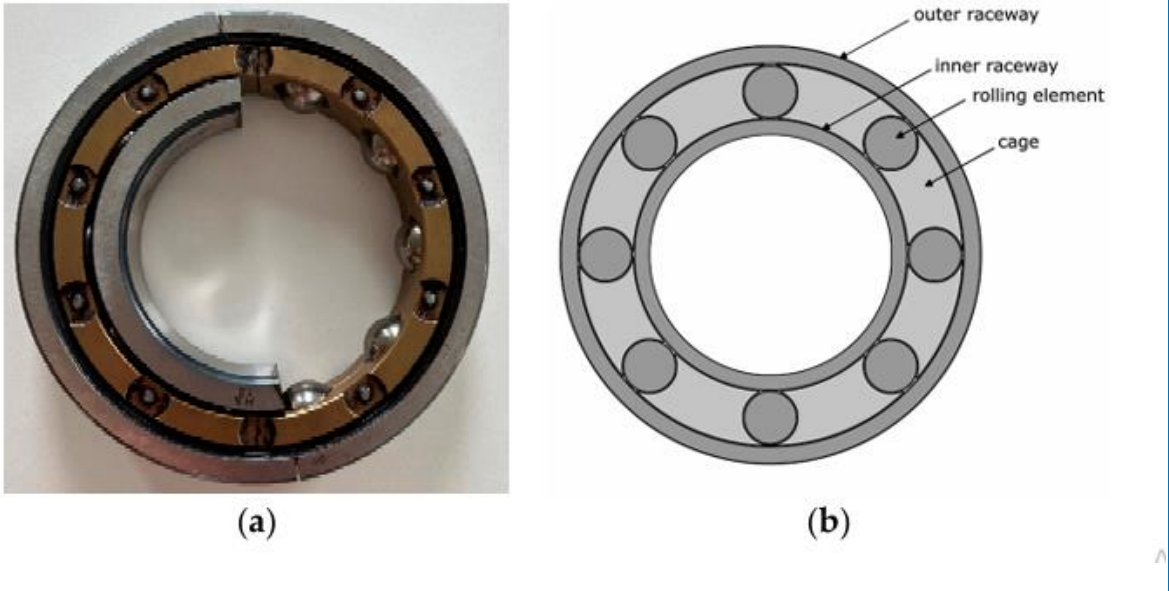


Fig.4 : a) picture for broken bearing , b) representation of bearing elements [6]



Fig. 5: Normal and faults types in bearing .[11]

3.2.2 Eccentricity faults

Three-phase induction motor Eccentricity is a frequent problem that can have a big impact on the motor's effectiveness and performance. An imbalanced load, problems with the electrical connection, or even faults in the motor's component parts might cause misalignment. Frequency deviation is one of the primary misalignment issues. It can cause variations in the motor's speed and torque output [11], [17].Stress is the main factor leading to Eccentricity in the motor, and it can result from several causes, which can be clarified in figure (Fig.6).

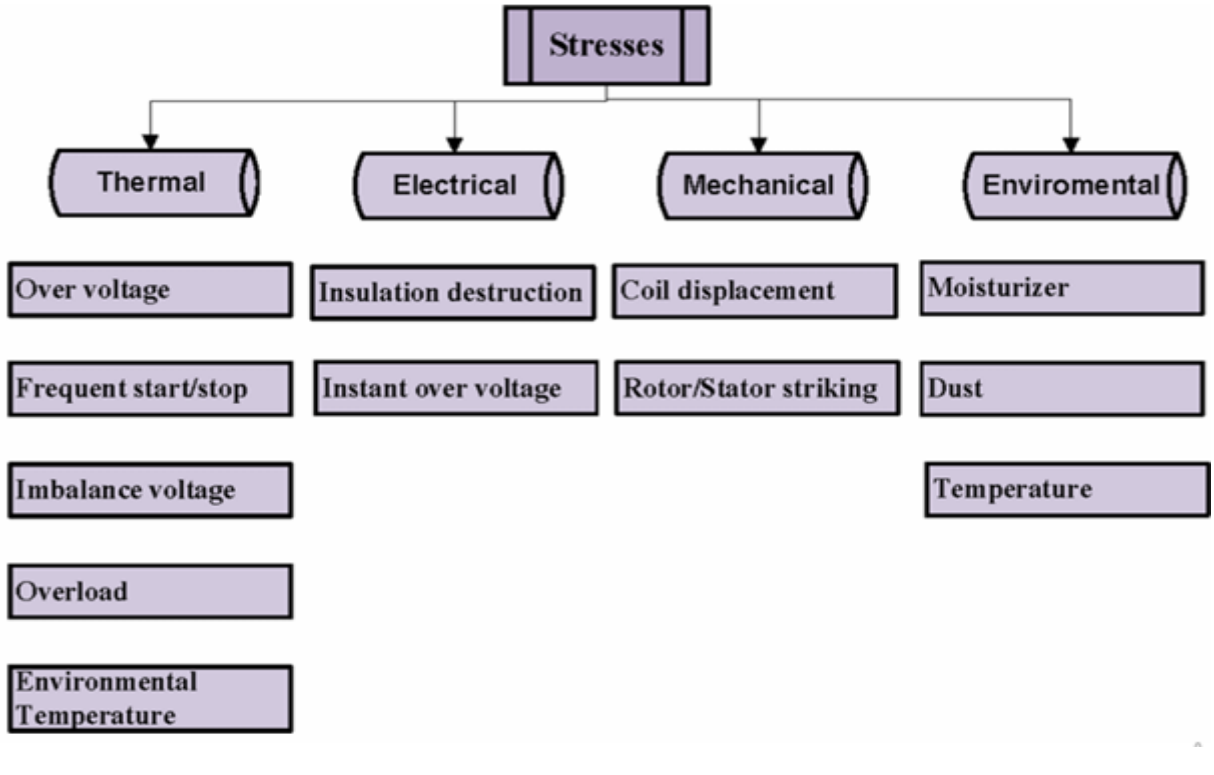


Fig. 6: Stress reasons at three-phase induction motor [6].

3.2.1 Load faults

When a three-phase induction motor is used under an uneven load, or when the motor applies more mechanical energy than it is rated to handle, this can create an imbalance in the current through each of the three phases. The result of this situation is a difference in current between each of the phases, and as a result the phase that receives the most current will experience a greater increase in copper losses, heat build-up in the windings of the stator, and reduced efficiency for the motor. If a motor is run in an imbalanced state for long periods of time, this will cause insulation degradation and could result in catastrophic failure of the motor. The most common causes for load faults are mechanical issues with the driven load (such as misaligned shafts or threaded plugs), mechanical blockages, or problems with the bearings of the driven load. Other factors, such as rapid changes in load demand, a lack of proper coupling between the motor and its drive, and connections to the drive that are improper can cause abnormal demands on the motor. Abnormalities can create unbalanced torque, unbalanced currents, and generate more vibration, thermal degradation and reduced efficiency. Therefore, proper and timely detection and diagnosis of load faults will help prevent overheating, ensure the reliability of motor operation, and increase the service life of three-phase induction motors.

NOTE: the faults according to EPRI (Electric Power Research Alliance) can be classified as shown in figure (Fig.7).

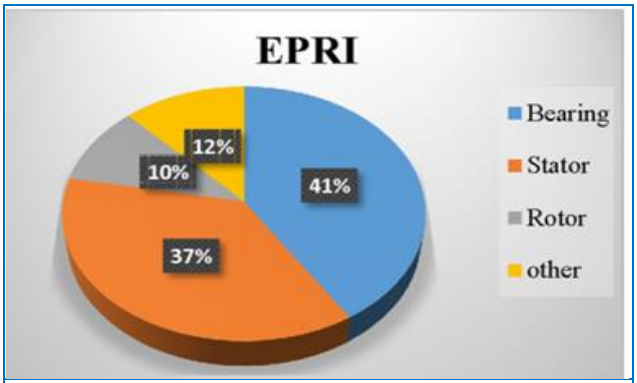


Fig. 7: Faults classifications in EPRI .[13]

Faults can be reclassified, the method of identifying them and the potential damages they may cause can be shown in the following table:

Table 1: Types of faults, methods of detecting, and potential effect

NO.	Fault type	How to Identify	Cussed by
1	Inter-Winding Short Circuit	Increased current, abnormal heating in the motor.	Insulation damage, high temperature, motor performance degradation.
2	Voltage Imbalance	Fluctuations in voltage between phases, reduced efficiency.	Increased energy consumption, abnormal vibrations, bearing damage.
3	Rotor Bar Fault	Decreased torque, unbalanced vibrations, and current variation.	Loss of efficiency, increased current, high temperature, motor damage.
4	Bearing Faults	Abnormal vibrations, noise, increased temperature.	Bearing wear, increased energy consumption, motor failure.
5	Misalignment (Eccentricity)	Unbalanced vibrations, abnormal noise.	Increased friction, rapid wear of mechanical parts.
6	Load Fault	Abnormal motor loading, excessive current draw, reduced torque.	Overheating, potential motor damage, reduced performance and efficiency.

4. Importance of Early Fault Detection in Induction Motors: [13], [14]

- Preventing Operation Failures: Early when communicated, results in reduction of the chances of unplanned operations shutdowns. - Reducing Costs: It can limit emergency maintenance and repairs cost. - Longer motor life: It can reduce stress and wear on motor internal components and their insulation system, windings, and bearing etc. - Operational Efficiency: Ensures the induction motor operates smoothly and at its optimal operating conditions. - Preventing Secondary Damage: It can prevent, while communicated to the system, minor mechanical or electrical problems from becoming secondary larger issues to other motor components or systems. - Improved Safety: It can reduce certain potential safety risks associated with heat and motor failures. - Energy Savings: It can eliminate associated wasteful energy usage associated with the mechanical or electrical problems.

5. Techniques to detect three-phase motor faults

Initially, it was up to human perception and observation to discover if the motor was failing [15]. Subsequently, a number of simple principles developed as the rationale for early fault detection, some of the more recognized include:

- Resistance Testing: measuring the winding resistance to detect open circuits or failed insulation
- Acoustic Analysis: recording the sound and listening for the sound of the motor to determine if any abnormal change had occurred
- Motor Current Monitoring: monitoring the current could detect abnormal deviations and under some conditions mechanically or electrically related failures
- Vibration Analysis: measuring vibration to detect mechanical failure such as misalignment or bearing failures
- Thermal Analysis: measuring temperature to determine failure due to excessive heat from electrical or overload issues
- Magnetic Flux: measuring the motor magnetically can determine stator or rotor failures that could not be discovered using other principles

Voltage Monitoring: measuring the voltage between phases to determine any imbalance or failure in electrical supply to the motor. There is much research and studies on practical methods for faults based on the principle found above; some follow individual principles while others combine two or more principles whenever possible to detecting.

5.1 Testing the insulation resistance (IR)

Insulation resistance testing is a significant hands-on experience utilized as a strong fault detection method for electrical faults in the stator and rotor windings. This test helps to recognize insulation breakdown, openings that can create short circuits or electrical leakage. Furthermore, an emphasis on insulating resistance will enhance the accuracy of the other diagnostic techniques for detection [16], [17].The main idea for this method can be explained in Fig.(8).
Since this test is easy to perform, generates insightful data, while being able to identify faults early, it decreases the probability of catastrophic failures. However, this test will only identify insulation-related failures, and it may not detect issues related to motor imbalance or mechanical failure. Furthermore, the testing will not be entirely accurate with poor environmental conditions.

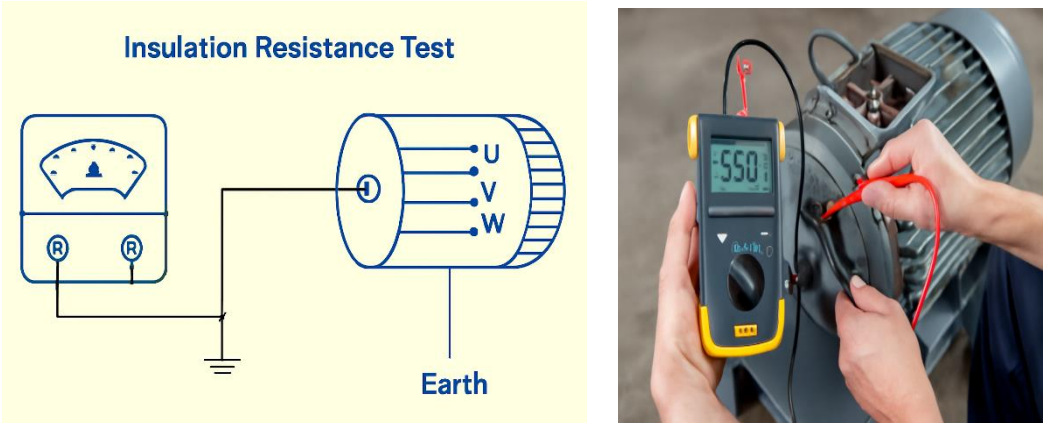


Fig.8: insulation resistance test.

5.2 Current analyzing

Because of its ease of use and low requirements, it is considered as the most widely used and popular method for detecting multiple faults in a three-phase motor. It mostly depends on the stator's current, and the situation can be described based on its investigation in the frequency domain [10]. [18], [19]..MSCA (motor current signal analyzed) principle can be explained by this figure (Fig.9).

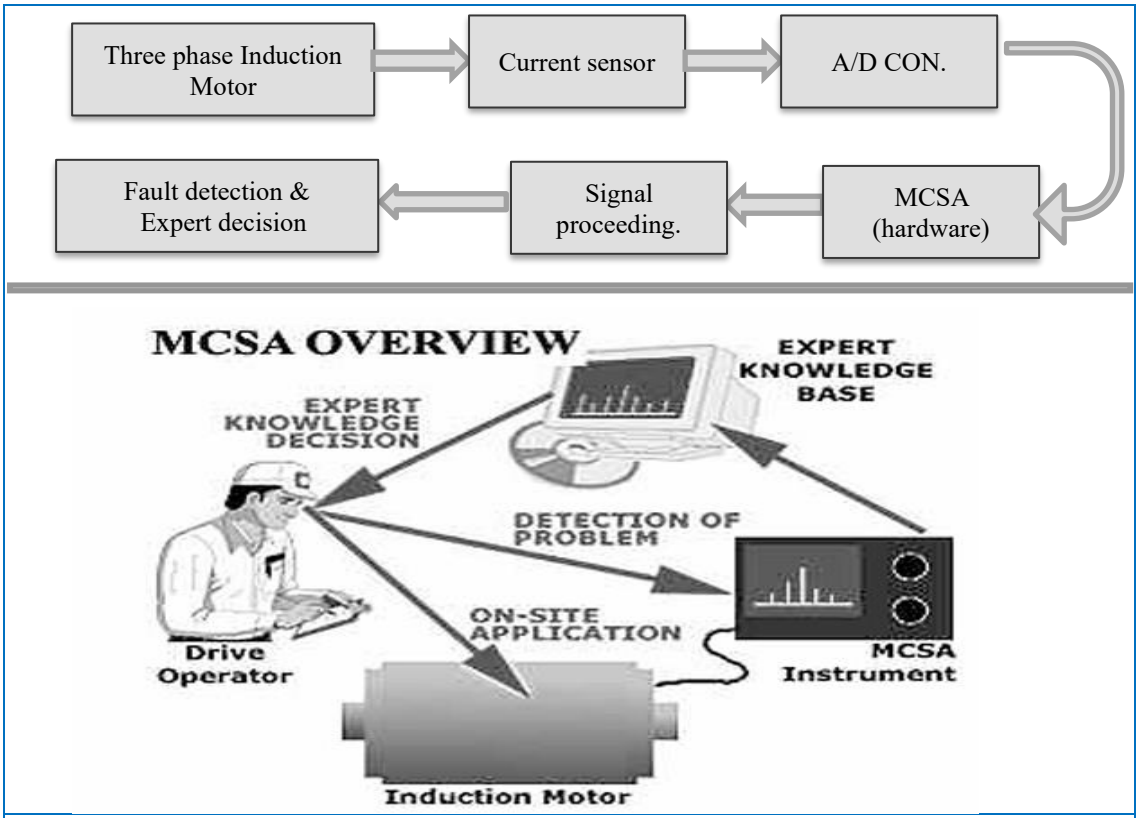


Fig. 9 a) working principle, b) MCSA strategy [10].

MSCA can be used for multi-detection of faults; it can be explained listed table 2.

Table 2: Types of faults detecting by MCSA.

NO.	Fault type	Brief Description	How It Appears in Current
1	Stator Faults	Damage to the stator windings or short circuits.	Increased harmonics in the current or waveform distortion.
2	Rotor Faults	Variance in resistance or broken rotor bars.	Sidebands around the fundamental frequency.
3	Supply failure	The current's three phases differ from one another.	Distortion in current waveform and abnormal harmonics.
4	Mechanical Faults	Mechanical deterioration or bearing wear.	Current frequencies that indicate to low mechanical cycle counts.
5	Misalignment	Misalignment of the motor shaft with the load.	Frequencies at 2x or 3x the fundamental frequency.
6	Load Imbalance	Unbalanced distribution of the load.	Phase imbalances cause current frequencies.

One of the many advantages of the MCSA technique is its non-invasive nature, which eliminates the need to shut down the motor in order to identify problems. Also, it costs less than other methods and is very accurate at finding mechanical and electrical problems early on, which helps to avoid big failures [20], [21]. The MCSA method works, but it has a lot of problems. It can't find small mechanical problems like bearing wear or an unbalanced load because it mostly looks for electrical problems. Also, in some cases, extra interference or electrical noise in the area around the analysis may make it less accurate [21], [23]. This technique has undergone several enhancements over time [24], the most significant of which are:

- Many studies have integrated digital filtering techniques with Motor Current Signature Analysis (MCSA) to enhance fault detection accuracy by removing electrical noise and interference.
- Analyzing the current across time and frequency using methods like the Wavelet Transform, which enables the identification of small mechanical problems like imbalance problems or bearing wear. This technique provides a better analysis of faults that may not be easily visible in traditional spectral analysis [25], [26].
- Enhancing the ability to detect electrical harmonics caused by failures like inter-turn shorts or deteriorating insulation. It's possible to easily and precisely identify current distortions in the electrical system brought on by harmonic interference by using harmonics analysis techniques. [24], [27].

5.3 Acoustic analyzing

Acoustic analysis is a method that involves monitoring and analyzing the sounds from an induction motor while the motor is in healthy operation, in order to detect any abnormal changes. As an example, these sound changes may suggest the potential for mechanical or electrical issue, including motor imbalance, bearing wear, or electrical failure. Some abnormal sounds might be whistling, knocking, or grinding, and may serve as a warning of a motor issue [28]. Sound monitoring from the motor under healthy operation is the basis for acoustic analysis. Sound waves can be recorded with microphones and/or acoustic sensors before being analyzed for their frequency and any unusual sounds using specific software. Sounds like squeaking or knocking may indicate an electrical problem or mechanical parts issues, including misalignment or bearings. This approach even allows early detection of issues and maintenance planning and reduced repair costs, as the issue

can often be discovered without having to stop the motor or take the motor offline [29],[30]. A simple diagram explains the working principle of acoustic analyzing shown in figure (Fig.10).

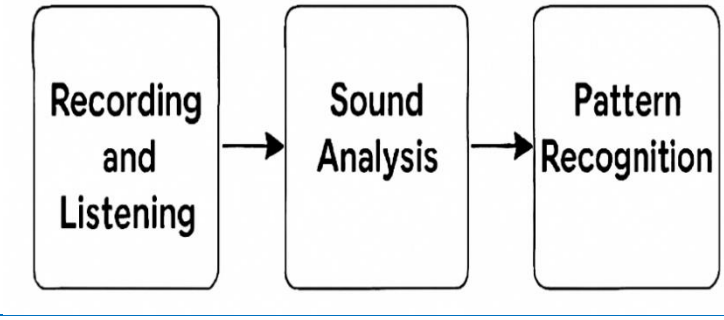


Fig. 10: Acoustic technique working principle.

A number of studies indicate that this method can identify several faults that a three-phase motor may experience can be explain in table 3.

Table 3: Types of faults detecting by Acoustic technique

No.	Fault type	How to detected
1	Bearing Faults	Unusual sounds like squeaking or knocking brought on by bearing wear or damage.
2	Imbalance Faults	Unusual or irregular noises indicating misalignment or imbalance in the motor.
3	Electrical Faults	Distorted sounds or buzzing, which can indicate issues like insulation failure or short circuits.
4	Misalignment Faults	Squealing or irregular noises caused by misalignment between the motor and its load.
5	Rotor Faults	Unusual sounds brought on by damaged rotor bars or rotor mechanical problems.

Acoustic monitoring is a non-invasive approach that can detect faults early, without having to stop the motor. The method is easy to apply with basic equipment such as microphones and acoustic sensors [31]. However, the method can be sensitive to external noise, which may disturb detection accuracy. Lastly, careful interpretation of sounds requires skilled understanding to accurately identify faults.

5.4 Vibration analyzing

Vibration analysis is based on measuring and monitoring the vibrations produced by the motor while operating. Any abnormal change in the vibration pattern can signal an onset of mechanical problems in the induction motor [32], [33]. The motor has sensors that will store data on vibration before it is analyzed for abnormal behaviors, which may indicate mechanical issues such as imbalance, misalignment, or bearing damage. Early defect detection is achieved by looking at the vibrations frequency and amplitude [34]. Vibration method can be describing its working principle as shown in Fig.11.

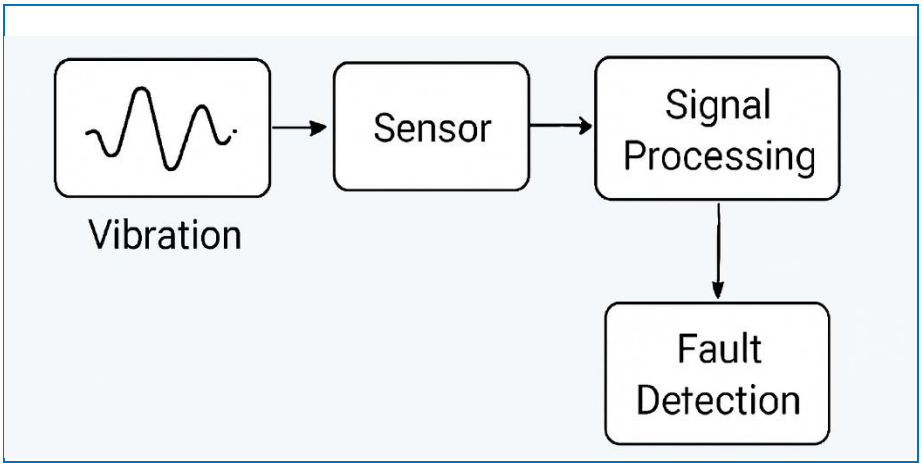


Fig. 11. : Vibration technique working principle

A number of studies indicate that this method can identify several faults that a three-phase motor may experience like:

1. Bearing fault: characteristic frequency patterns within the vibration signals suggest that the bearings are either worn or damaged. These patterns can help identify bearing issues such as ball damage or damage to the inner or outer race.
2. Imbalance Faults: If the motor is not balanced, there will be uneven vibrations at particular frequencies. The base frequency or harmonics of the imbalance is where the abnormal vibration would be detected.
3. Misalignment Faults: Abnormal vibrations occur because of misalignment in the motor's components or in the alignment or misalignment with the load on the motor. Misalignment of components generates vibrations that will have abnormal frequencies. The degree of misalignment can be interpreted by the abnormal frequencies.
4. Electrical Faults: The changes in the vibration patterns may indicate electrical problems to the mechanical parts due to electrical issues. Vibration signals may reflect interruptions from the motor because of faults such as winding issues and insulation failures.

Vibration analysis is an effective way to identify locations of looming problems within motors, such as bearing wear and imbalance [33], [34]. The process is considered non-destructive because monitoring occurs without turning the motor off, reducing downtime while allowing identification of failure early on to prevent catastrophic failure. Abnormal signals can reflect outside effects, such as noise, which may constrain the accuracy of an analysis. Furthermore, successful detection of faults based on vibrations requires a skilled analyst.

5.5 Thermal analyzing

Monitoring the motor's operating temperature is crucial to thermal analysis. Temperature variations assist in the identification of mechanical or electrical problems with the motor. Because extremely high temperatures can be caused by faults like overloading or deteriorating electrical insulation, high motors temperature is considered as one of the primary signs of failure[35],[36].Variations in temperature at many locations, including the stator and rotor, are recorded while the motor is operating. Following that, these temperature data is compared with normal operational conditions. Unusual temperature spikes may be a sign of problems like overloading or faulty insulation. Thermal analysis assists in detecting any

problems before they cause serious motor harm by detecting these temperature variations early. Thermal method can be describing its working principle as shown in figure (Fig.12).

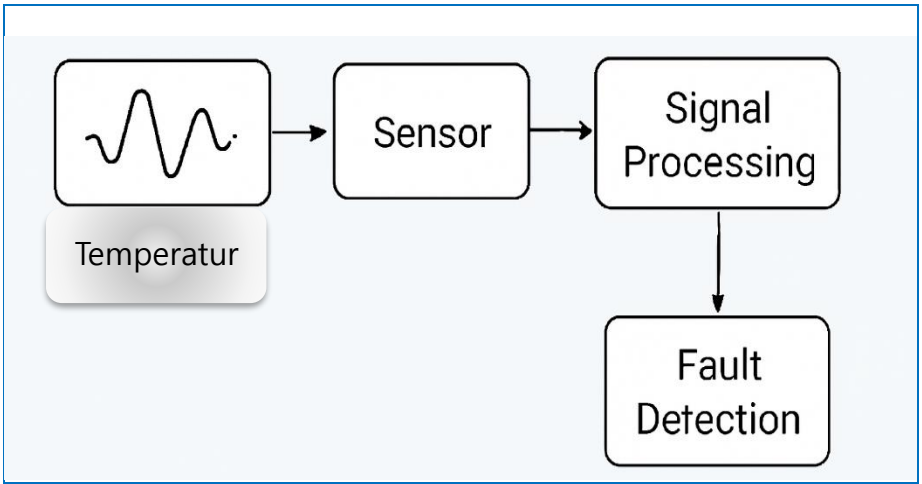


Fig. 12. : Thermal technique working principle

A number of studies indicate that this method can identify several faults that a three-phase motor may experience like:

1. Insulation Failures: The motor may be overheating in specific parts, which could be a sign of electrical shorts or damaged insulation.
2. Overload Faults: An excessive increase in temperature throughout the motor indicates that it is operating above its capacity.
3. Bearing Faults: high temperatures in the bearing area as a result of wear or excessive friction
4. Electrical Faults: an unusual increase in temperature due to electrical short circuit or failed windings in certain windings or motor components.

The detection images can be shown in Fig.(13).

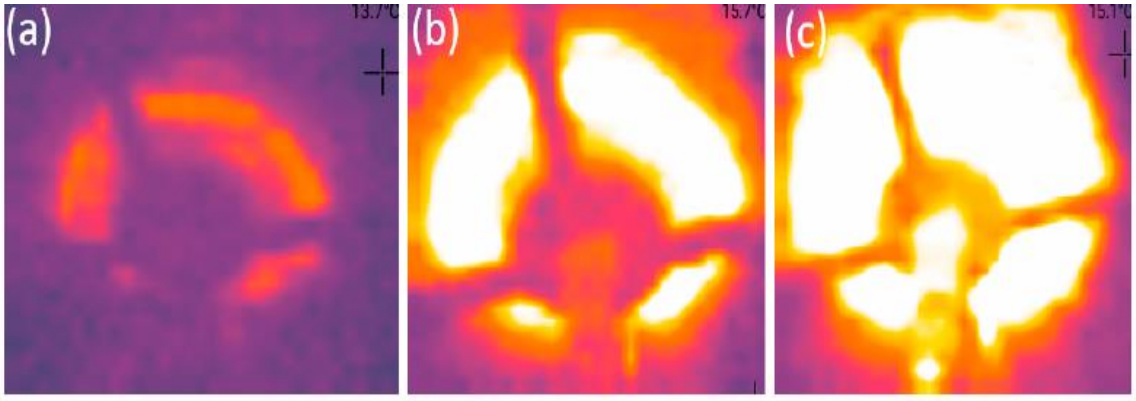


Fig. 13: thermal images of induction motor a) normal state. b) Overload state. c)Fault condition .[38]

Thermal analysis is a continuous, non-invasive technology for detecting induction motor faults and identifying problems (overloads, & bearing & insulation problems) before they lead to failure, preventing the motor from needing to be stopped for investigation. Its extreme accuracy in detecting temperature issues supports preventive maintenance. However, thermal monitoring entails specialized equipment (e.g., infrared cameras, temperature sensors) and is influenced by external factors (i.e., outside temperature) making it more challenging and more costly to implement.

5.6 Magnetic flux analyzing

A system that records and monitors the internal flow of a motor's magnetic flux while the motor operates is made possible through the use of magnetic flux sensors. The motor performance is directly influenced by the magnetic flux, and any unusual variation from its normal flow can signal mechanical or electrical concerns [39],[40]. Magnetic flux analysis entails measuring the flux at designated components of the motor employing specific sensors. The sensors gather continuous information during motor operation, from which measurements are taken—sensors exhibit an unusual number of measurements in variables that require further analysis to determine abnormality from an expected condition. Abnormal variation in magnetic flux indicates potential issues, such as an insulation failure or rotor issue, necessitating further analysis to identify the potential fault and exact location for accurate diagnosis and early detection [40], [41]. Magnetic flux method can be describing its working principle as shown in figure (Fig.14).

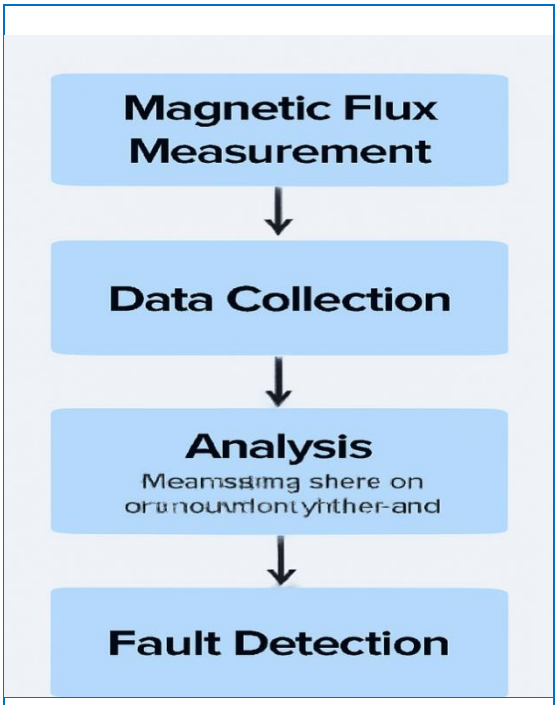


Fig. 14. : Magnetic flux technique working principle

A number of studies indicate that this method can identify several faults that a three-phase motor may experience depend on the analyzing and main relationships between the magnetic flux with current and with the speed can be described many types of faults like:

1. Insulation Failure
2. Rotor Faults
3. Stator Winding Faults
4. Mechanical Imbalances

Among the many benefits of magnetic flux analysis is its non-invasive fault identification, which eliminates the need for motor shutdown or disassembly. t is one method to obtaining early detection of mechanical or electrical defects. The process takes place before a significant most known issue occurs as detection of the issue occurs before damage starts—a quasi-predictive maintenance that allows early defect detection and potentially reduced costs to complete repairs. However, it has drawbacks, including the need for instrumentation and sensors for advanced measurement and analysis that can increase the cost. In addition, this method of analysis may contend with outside magnetic interference in the motor system, and the magnetic flux data will take time to analyze, and the person analyzing the data will require specific knowledge to interpret the data appropriately.

6. Classical control and fault detection in a three-phase induction motor

Classical controllers like V/F controller, PI, PID and other controllers, its normally used at three phase induction motors but by indirect way , for more explaining its used for current adjusting ,torque controller , speed controller and for enhancement efficiency especially during abnormal value due to the fault moment to make optimization as it can [42], [43].

Classical controllers used for:

- Monitoring and controlling motor performance: To keep the motor's performance within ideal range, a controller is utilized to modify factors like speed, current, or torque. A fault may be indicated if these variables exhibit unusual variances, such as an increase in current or a change in speed.[1]
- System response controller's parameters can be changed to balance motor performance when a fault occurs, such as higher vibrations or excessive temperatures.
- Enhancing system reaction in the event of a failure: Once a possible failure has been detected, the controller can be modified to lessen the impact of the failure on the system or stop more impacts.

On the other side (if it used for detection of fault) it fails to provide an accurate diagnosis of the problem, It has trouble identifying and distinguishing between mechanical problems in addition to impacts from the environment.

7. Artificial intelligence and fault detection in a three-phase induction motor

Due to the useful abilities of Artificial Intelligence (AI), the implementation of AI in industrial and electrical applications is rapidly increasing [44]. The recent rise of AI-based techniques for monitoring and diagnosing faults within electric motors has gained considerable interest because these techniques excel at analysing large amounts of complicated data, and modelling the non-linear behaviour of systems. AI-based techniques are among the most sophisticated available today, allowing for increased speed and accuracy in the evaluation of motor data for problem identification and automatic decision-making rather than depending on manual inspection. AI employs many types of methods, including machine learning and neural networks, to interpret the information generated by motors (e.g., currents, vibrations, temperatures, magnetic flux, etc.) [45], [46]. These methods can enable the extraction of relevant features from raw signals, as well as allow AI systems to learn the relationships between operating conditions and the faults. Because of these abilities, AI systems can differentiate between normal and abnormal operation of motors, even under varying conditions of load, speed, and system response time.Sensor-based data collection consists of measuring a variety of motor parameters (e.g., current, temperature, and vibration) at one point in time. Once collected, this data is preprocessed and input into AI models that use intelligent methods to interpret the data in order to search for trends and classify the operating conditions of the motors, as well as to find any atypical results associated with motor operation. Abnormalities may indicate possible failures (e.g., a mechanical imbalance, degraded insulation, or worn-out bearings) associated with motor operation. By allowing for earlier detection of failures (and better resource planning), artificial intelligence has enabled the enhanced reliability, reduced maintenance costs, and increased safety of systems driven by electric motors. The above principle for AI can be shown in figure (Fig.15). The AI system can learn and identify faults based on patterns it observes in past motor behaviors because it has been taught using historical fault data. After training, the AI model can identify early indications of problems before they result in serious harm, allowing for the scheduling of preventive maintenance.

There are many artificial intelligence techniques for identifying three-phase motor faults; the most significant ones are shown in the table 4 that follows.

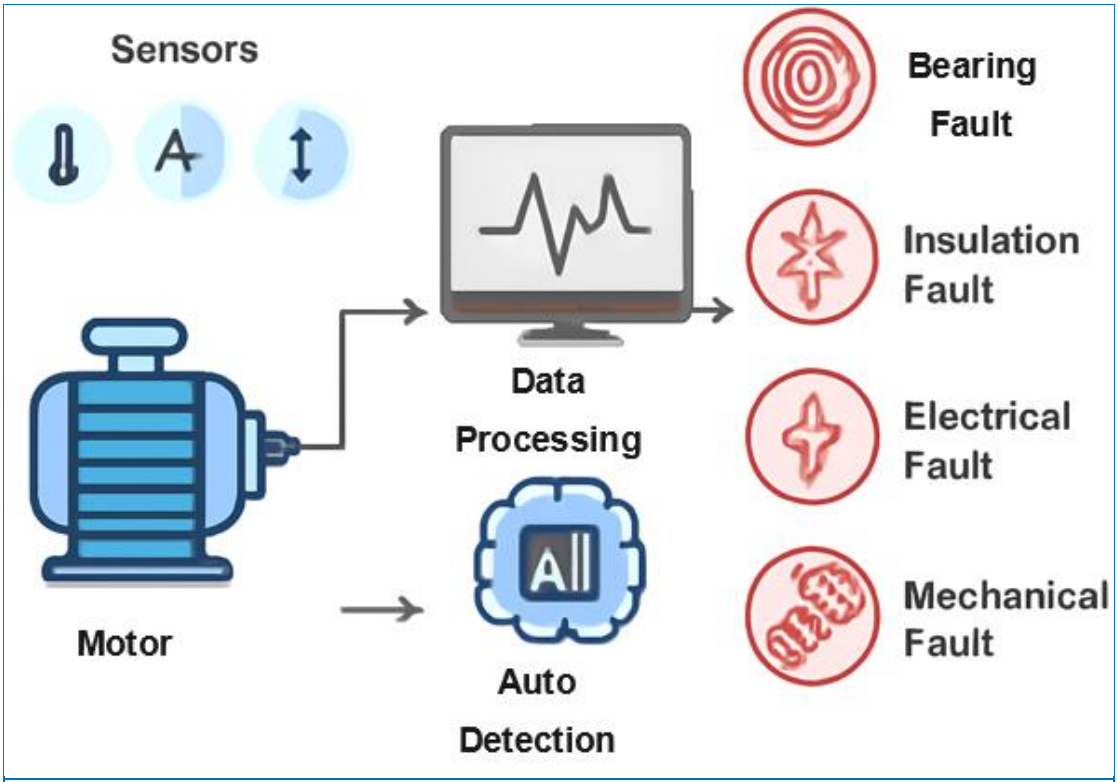


Fig. 15: AI working at faults detection.

Table 4: Most common AI artificial techniques and fault detection.

Technique	Used for	Advantage	Disadvantage
Fuzzy logic control (FLC) [48],[49].	It is employed to identify confusing or unclear system states, such as how it moves between total failure and full health.	-Assists with dealing with changing or incorrect information -High interpretive flexibility.	Designing an efficient system is challenging, and interpreting the results requires a great deal of skill.
Artificial Neural Networks (ANN) [46].	In order to find defects, it is used to analyze data and find patterns in data like current, vibrations, and heat.	-High classification accuracy of the data. -The ability to recognize future fault.	- Needs a lot of training. When used with several motors, it can become complicated.
Convolutional Neural Networks (CNN).[50],[51]	Its primary application is in image or spatial data processing, such as finding faults in infrared pictures.	High precision in picture applications; perfect for processing data with temporal or spatial patterns.	-It takes a lot of training time. -The inability to comprehend the rationale behind the choices made.
Machine Learning[52],[53].	It uses techniques like regression, SVM, and neural networks to analyze vast amounts of data and find patterns associated to faults.	-Enhances detection accuracy and makes vast data analysis possible. -Continuous training allows for the gradual accumulation of experience.	-To properly train the model, a large amount of data is needed. -Algorithms require time for learning.

Deep Learning.[54], [55].	It is employed for analyzing large amounts of data to identify minor patterns that might not be obvious, like bearing wear.	-Effective at deciphering complex data. -Able to identify faults that are hard to recognize with conventional techniques.	-It needs a lot processing power. -Sometimes it's hard to interpret the results.
Clustering Algorithms [56].	It is employed for collecting data with comparable patterns and to find abnormal faults or hidden trends.	-Assists in identifying unconventional faults. -It is not necessary to be knowledgeable of the faults beforehand.	-It might not be able to give exact information about faults. -Determining the ideal number of clusters is difficult.
Regression Algorithms [57].	It is employed to find the mathematical relationship between possible failures and variables like torque or current.	-Accurate continuous data analysis. -Simple to use in systems with simple data.	-With complicated systems, it might be less accurate. -Categorical data is not handled correctly.
Predictive Analytics [58],[59].	Regression analysis and statistical algorithms are used to predict possible future failures based on historical data.	-Identifying future faults with accuracy. -Minimizes unplanned downtime.	-Depends largely on historical data. -May not operate effectively with limited data.

There are several benefits of using artificial intelligence in the practice of three-phase motor fault detection, but the most significant ones are: [60], [61]

- Early identification of faults.
- High level of accuracy in diagnosis.
- Multifaceted analysis.
- Fewer demands on human knowledge.
- Real-time diagnosis and ongoing observation.
- The ability to predict maintenance.
- Analysis of big data.

7.1 Hybrid Artificial Intelligence Techniques for Fault Diagnosis

As industrial systems become increasingly complex and demand higher reliability levels, intelligent fault diagnosis of three-phase induction motors has garnered considerable interest. Traditional approaches for diagnosing faults in industrial systems utilize either a signal thresholding or a classical spectral analysis method but are generally less accurate when used in variable operating conditions and noisy environments.[62] The development of hybrid artificial intelligence (AI) systems has provided an advanced method for diagnosing faults in three-phase induction motors through a combined value of several intelligent techniques combined into one diagnostic method.Hybrid AI systems will integrate machine-learning or intelligent-optimization algorithms and signal-processing methods. The first step will be to extract the time-domain, frequency-domain, or time-frequency features of motor signals (i.e. stator current, vibration, thermal measurements) through methods such as Fast Fourier Transform (FFT), Wavelet Transform (WT), or Empirical Mode Decomposition (EMD).[63],[64] The second step will be to input these features into an intelligent classifier (artificial neural network [ANN], support vector machine [SVM], or deep-learning model), resulting in higher-performing intelligent classifiers when paired with the optimization algorithms (genetic algorithms [GA], particle swarm optimization [PSO], or fuzzy logic

system).Using a combination of both traditional and advanced technologies typically produces significant advantages to the diagnostics process.[65] AoPs provide improved diagnostic reliability, adaptability and accuracy with respect to load and speed. By utilizing a combination of complementary techniques, hybrid diagnostic models are capable of overcoming various sources of uncertainty, non-linearity and overlapping fault signatures experienced by a majority of three-phase induction motors. In addition to enhancing diagnostic performance, hybrid systems also allow for early fault detection, as well as identification of the severity of common motor failures (i.e., stator windings, broken rotors, bearings, and eccentricities).Research studies have shown hybrid intelligent diagnostic technologies have proven superior classification performance compared to singular technology methods alone when it comes to determining how well the diagnostic system generalizes outside the test parameter set. Therefore, a systematic approach which implements hybrid artificial intelligence tools for developing automated, reliable and real-time fault diagnostic systems for three-phase induction motors is an avenue of great promise for future use in industrial applications.

8. Discussion

- All the Traditional methods that were explained considered an inverse and does not need to stop the motor, but the main differences are

Table 5: Traditional methods of fault detection characteristics.

Method	Working principle	Faults detected types (optimally)	Advantages	Disadvantages	Accuracy
Current Analysis	Measuring and analyzing motor current	- Winding Faults -Insulation Failures - Overload Faults	- affordable - provided ongoing observation	It only works with electrical problems, while mechanical problems could cause it to fail.	High accuracy for detecting electrical faults
Acoustic Analysis	Sound sensors or microphones are used to record sounds to analyze unusual behaviors.	Faults related to bearings, imbalance, misalignment, and electrical fault at a lesser proportion.	Early fault detection requires simple equipment.	- Sensitive to external noise. - Specialized interpretation is necessary.	Medium; it is reliant upon experience and environment.
Vibration Analysis	detecting unusual motor movement patterns via measuring vibrations.	Same to above.	Excellent in detecting mechanical faults	Same to above.	High specially in detecting mechanical faults
Thermal Analysis	Thermal sensors are used to monitor temperature changes to detect hot spots.	- Insulation Failures - Overload Faults - Bearing Faults	Provides good detection of a number of electrical and mechanical faults	-It is affected by environmental factors. -It requires special equipment.	Mid. To high , it depend upon environment and used equipment

Magnetic Flux Analysis	Measuring and analyzing motor magnetic flux	- Insulation Failures - Rotor Faults - Stator Faults - Winding Short Circuits	Very good detection of a number of electrical and mechanical faults	- It requires special equipment. - Specialized interpretation is necessary.	Highest

- After reviewing the details of traditional methods and the artificial intelligence, it is possible to compare them based on several factors (criteria) as shown in the table (table6).

Table 6: Comparison between traditional methods an AI at fault detection characteristics.

criteria	traditional methods	artificial intelligence (AI)
The technology employed(most common)	- Acoustic analysis - Current analysis - Vibration analysis - Thermal analysis - Magnetic flux analysis	- Artificial Neural Networks (ANN) - Deep Learning - Convolutional Neural Networks (CNN**)** - Fuzzy Logic - Reinforcement Learning
How it is work?	Observing motor running variables like temperature, sound, vibrations, and current to detect any abnormal behavioral changes.	Intelligent algorithms are used in big data analysis to identify anomalous patterns or predict failures.
Detection accuracy	-Efficient in identifying major faults. -Less precise in identifying minor fault or early detection.	Highly accurate in identifying faults early on, even those traditional methods might miss.
Cost	-Low cost -Typically needs essential devices like thermometers or microphones.	-Expensive -To train models, accurate sensors and a lot of processing capacity are needed.
Early detection	Limited: It could be challenging to find very early faults that don't have a big impact on performance.	Extremely successful in identifying faults early on before serious damage is done.
Ability for predicting faults.	Direct fault detection is the only method available; failures cannot be predicted.	Capable of predicting future problems by using historical data and the motor's current behavior.
Adaptability and flexibility	Limited ability to handle new or unusual situations.	Extremely adaptable and capable of adjusting to unexpected failure patterns or changing situations.
Ease of implementation	Implementation is really easily done and only needs simple equipment.	Implementation is difficult and necessitates the availability of large databases for model development as well as algorithm training.
Response to noise	Sensitive to outside noise, which might affect the accuracy of the measurement.	More noise-tolerant, yet handling it could require extremely complex techniques.

Requirements for experience and knowledge	While a thorough understanding of artificial intelligence is not necessary, it requires for hands-on expertise in traditional data analytics.	Advanced understanding of artificial intelligence and large-scale dataset training are required.

9. Conclusions

The article emphasizes the importance of employing fault detection methods that are designed for the different types of electrical machine failures. Several different types of electrical machine faults in detail, including eccentricity, rotor faults (broken rotor bars and end rings) and faults in the stator or rotor, and bearing faults. In addition, the article explained in detail the very efficient traditional methods for fault detection, however these methods often fall short of predicting the failures allowing for the introduction of artificial intelligence, through machine learning or deep learning. With AI, problems can be identified before failure occurs, consequently saving thousands in maintenance and down time. Despite these advantages, the need for specialist equipment and substantial installation costs remain barriers to widespread implementation . Traditional methods are still very useful in many settings, however they may miss faults that are slight or complex , therefore AI based resolutions are a desirable alternative. A feasible solution is combining artificial intelligence with traditional methods, creating a hybrid approach that relies on the pros and cons of each system.

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