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Diagnosis of Induction machine stator faults using stator currents harmonics

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Dedication

I dedicate this fruit of work:
To my mom and dad who got all the credit
To my brothers and all the family.
To all friends.
To all my teachers
To all my colleagues and special regiment
"electric machine".
To all of you a big thank you.
to my friends << Alaa eddine , Ismail >>
whom I thank for
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watahala.

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this dissertation.

NOTATION AND SYMBOLS

Ns: number of stator turns per phase

Ωs = synchronous speed

Fs = power supply frequency

p: number of pole pairs

g = slip

Ω = the rotor speed

AM = asynchronous machine

f.m.m = magnetomotive force

RSH = rotor slot harmonics

Irm = *maximum rotor current value*

TH = time harmonics

RBFH = Harmonics of Rotor Bar Fault

EFH = Eccentricity Fault Harmonics .

Irk= current in the rotor loop

Nr: number of rotor bars.

Ia, Ib, Ic: stator phase currents

φs: magnetic flux per pole created by the stator current

φabc: stator fluxes [wb]

Vabc: stator voltages [V].

FFT: Fast Fourie Transform

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General Introduction

The reliable operation of induction machiness is crucial for various industrial applications. However, these machines are susceptible to faults, which can lead to significant downtime and costly repairs. Timely detection and diagnosis of stator faults is therefore essential to ensure the efficient and uninterrupted operation of induction machiness. In recent years, there has been growing interest in utilizing stator current harmonics analysis as a diagnostic tool for identifying stator faults. This introductory section provides an overview of the importance of diagnosing stator faults and outlines the role of stator current harmonics analysis in fault detection.

Stator faults in induction machiness can arise from various causes, such as insulation degradation, winding short circuits, or mechanical damage. These faults can lead to abnormal machine behavior, including increased vibration, reduced efficiency, and even complete machine breakdown. Detecting stator faults at an early stage can prevent catastrophic failures, minimize downtime, and reduce repair costs. Therefore, developing effective diagnostic techniques is crucial to ensure the reliable and safe operation of induction machiness[56].

Stator current harmonics analysis has gained prominence as a diagnostic technique for detecting stator faults in induction machiness. When a stator fault occurs, it introduces asymmetry in the machine's magnetic field, resulting in harmonic components in the stator current. By analyzing the amplitude and frequency content of these harmonics, it is possible to identify the presence and severity of stator faults. Stator current harmonics analysis offers several advantages, including non-invasive monitoring, real-time fault detection, and the ability to diagnose various fault types.

This method of diagnosis involves obtaining the constant current signal using appropriate sensors, and then analyzing the signal in the frequency domain. Various techniques can be used to extract and analyze harmonics, such as Fourier analysis, wavelet transform, or period chart analysis. The obtained harmonic components are compared with predefined thresholds or reference values to determine if any faults are present and to assess their severity [57].

The dissertation has three chapters. In the first chapter, we present the causes and the natures of the various defects and also the diagnostic methods and the model of the induction machines, in a squirrel cage motor.

In the second chapter, we will provide an in-depth study of the types of time harmonics.

In the third chapter, we will present the spectroscopy of stator currents and their time harmonics using the fast Fourier transform (FFT), in addition to the most sensitive time harmonic detection.

Chapter I

State of the art on fault diagnosis in the induction machines

I.1 Introduction

Our study in this chapter will begin by introducing the induction machines. We will then study various faults that may affect it, including fixed part errors, moving part faults, bearing faults, and mechanical faults. Finally, we will present the most commonly used methods for diagnosis, including monitoring, detection, recognition, and fault location determination.

I.2 Induction machines

An induction machines, also known as an induction machine, is an electrical machine that converts electrical energy into mechanical energy or vice versa through electromagnetic induction. Unlike synchronous machines, which rely on a fixed relationship between the stator and rotor magnetic fields, induction machiness do not require a direct electrical connection between the stator and rotor. Instead, they rely on electromagnetic induction to create a rotating magnetic field in the rotor, which then interacts with the stator to produce torque. Induction machiness are widely used in various applications, including electric motors for industrial and household appliances, as well as in power generation and transportation systems.

I.2.1 Constitution of the induction machines

The induction machines, often referred to as an induction motor, consists of a stator and a rotor made of silicon steel laminations with slots in which windings are placed. The stator is fixed and contains windings connected to the power source. The rotor is mounted on a rotating shaft. Depending on whether the rotor windings are accessible from the outside or are permanently closed on themselves, two types of rotor are defined: wound or squirrel-cage. However, we assume that its structure is electrically equivalent to that of a wound rotor with windings short-circuited [1].

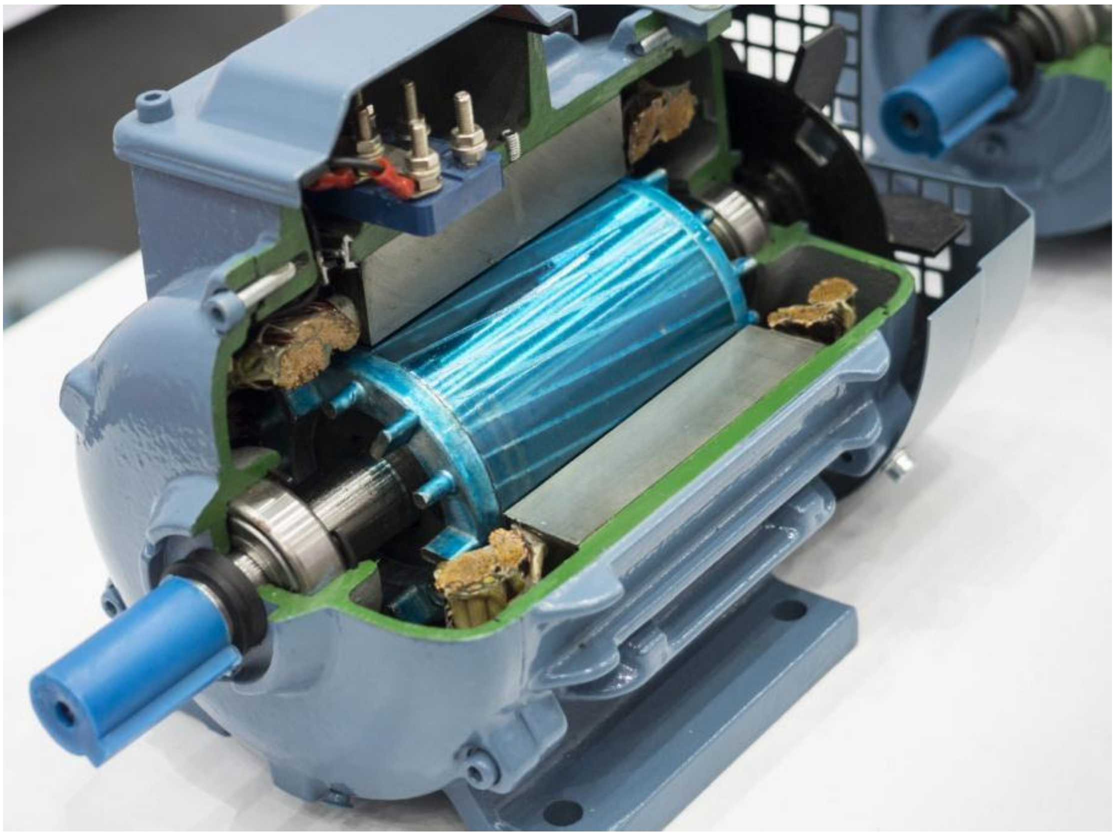


Fig. I.1 Induction machines [14]

The constituent elements of a squirrel-cage induction machines are illustrated in the Figure I.2.

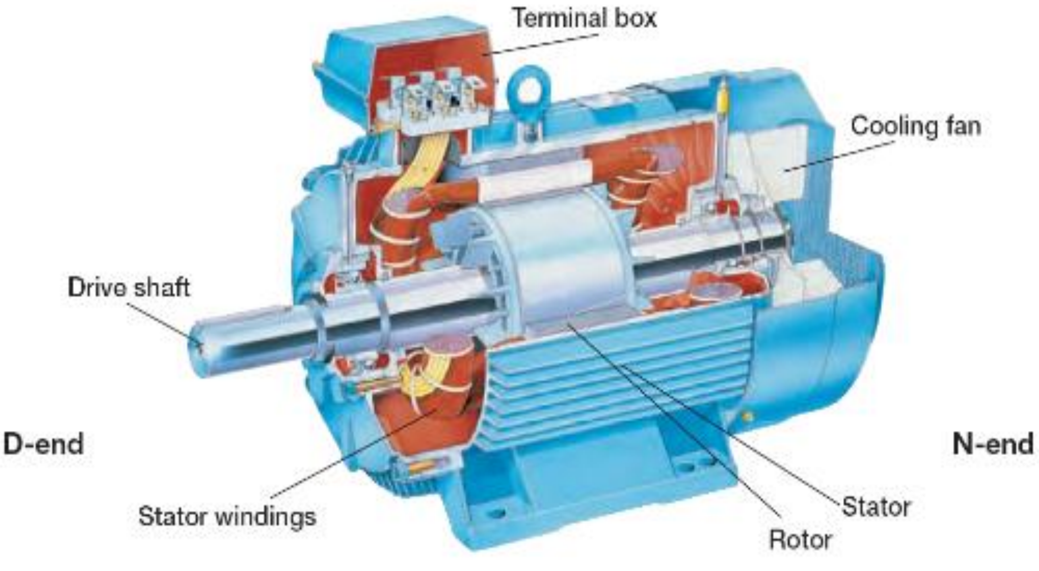
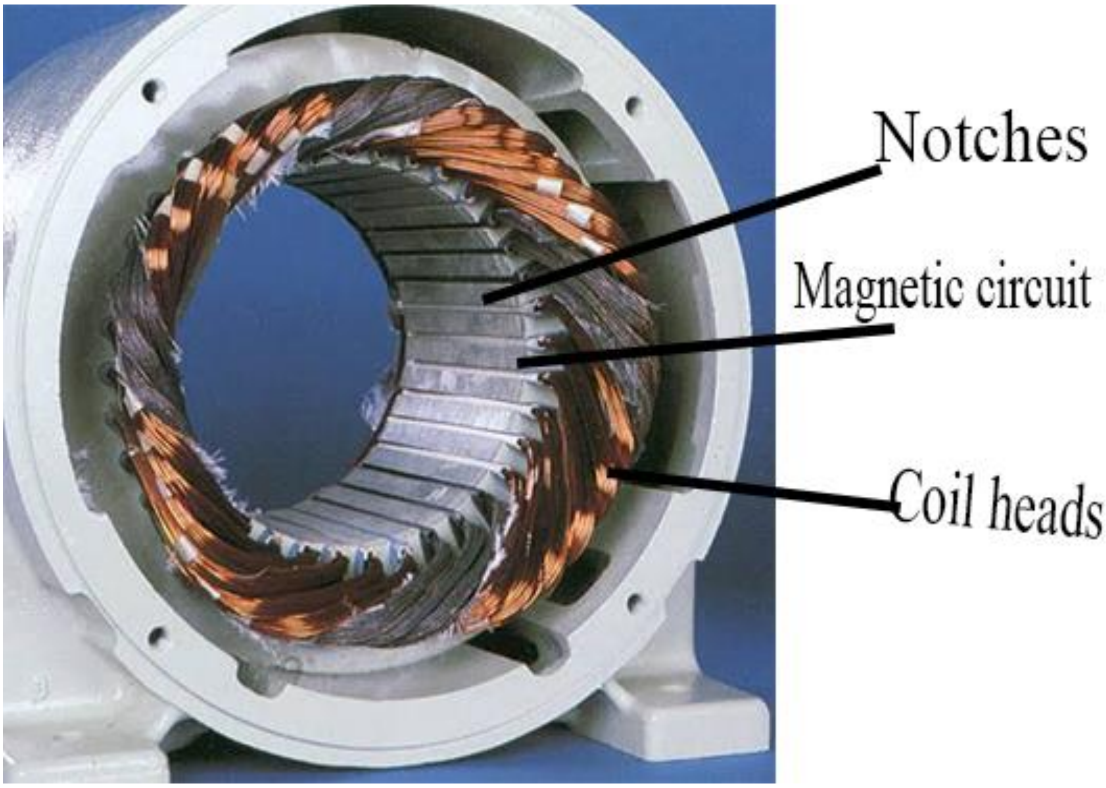


Fig. I.2 Components of a squirrel-cage induction machines [15]

I.2.1.1 Stator:

he stator is composed of a wound winding that is distributed in the notches of the magnetic circuit, as shown in figure (I.3). The magnetic circuit is made up of a stack of sheets that have notches cut parallel to the machine's axis. The stator winding can be divided into two sections: slot conductors and coil heads.



FigI.3 Stator of an asynchronous motor [16]

I.2.1.2 Squirrel cage rotor

The cage rotor consists of rotor bars that are connected through short-circuit rings, which enable the flow of currents between adjacent slot conductors. These rotor bars are uniformly distributed and form the rotor circuit. The rotor assembly, which includes the cage rotor, is placed within a magnetic circuit made up of stacked sheet metal discs on the motor shaft. This configuration is similar to that of a wound-rotor motor. Figure (I.4) illustrates the cage rotor and its placement within the magnetic circuit [2].

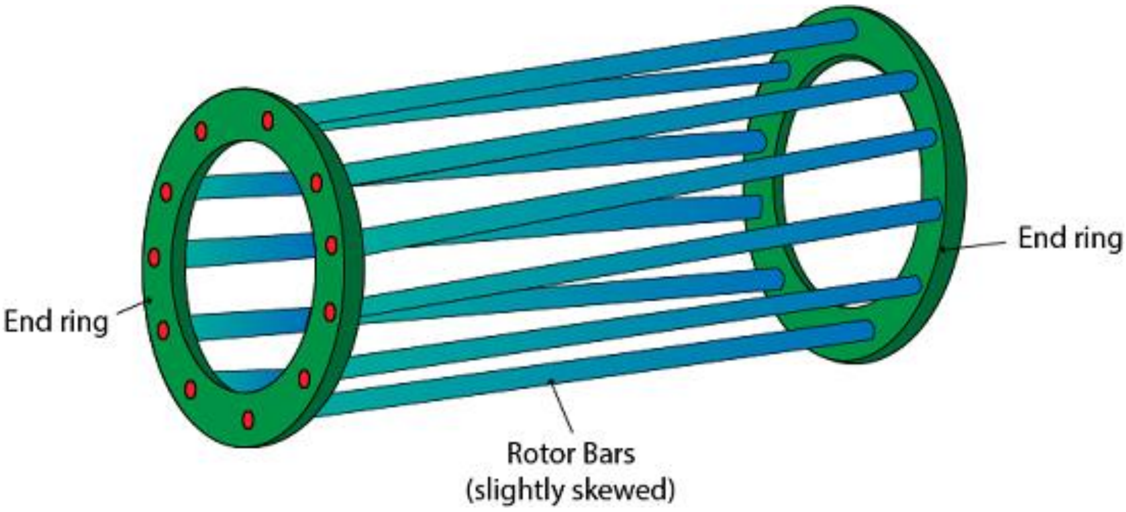


Fig I.4 Cage rotor [62]

I.2.1.3 Mechanical organs

In addition to the stator and rotor, induction machiness also have bearings and a shaft to support and rotate the rotor. The bearings allow the rotor to rotate freely and with minimal friction, while the shaft connects the rotor to the load being driven by the motor. The mechanical design of the motor is critical to ensure efficient and reliable operation in a variety of industrial applications

I.2.2. Operating principle

The operation of the asynchronous motor is based on the electromagnetic interaction between the rotating field created by the three-phase current supplied by a balanced three-phase network with pulsation ω on the stator windings, and the currents induced in the rotor winding when the conductors of the latter are cut by the rotating magnetic field (Lenz's law). This electromagnetic interaction between the two parts of the machine is only possible when the speed of the rotating field differs from that of the rotor [4].

asynchronous machine, the rotating magnetic field travels through the air gap between the stator and rotor at a constant speed called the synchronous speed (Ωs), which is directly related to the power supply frequency (fs).

$$\boldsymbol{\Omega s = \frac{\omega s}{p} = 60 * \frac{\omega s}{p}}$$

fs: frequency of the three-phase voltages of the supply network [Hz]
p : The number of pole pairs

A rotor that is short-circuited and swept by this rotating field will be traversed by induced currents (eddy currents), which subject it to electromagnetic forces of Laplace. The combination of these forces creates a driving torque that sets the rotor in motion (see figure I.4), with the rotor rotating in the same direction as the rotating field, but at a slightly lower speed ($\Omega < \Omega s$) [4], [5].

In fact, there is always a speed difference between the stator and the rotor, which is a particular characteristic of the AC motor. This difference is called slip (g), and is defined as the difference between the synchronous speed (Ωs) and the rotor speed (Ω). The slip (g) is given by: $g = \frac{\Omega s - \Omega}{\Omega s}$

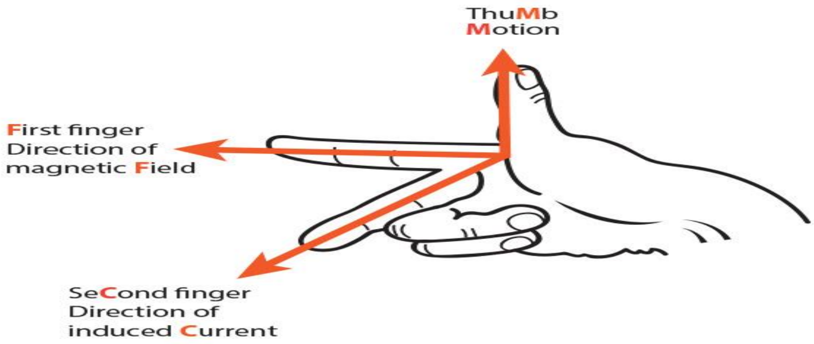


Fig I.5 Principle of operation of a three-phase squirrel-cage asynchronous motor [17]

I.3. Presentation of the various failures of the AM

I.3.1. Fault statistics

These faults are distributed according to the following figure:

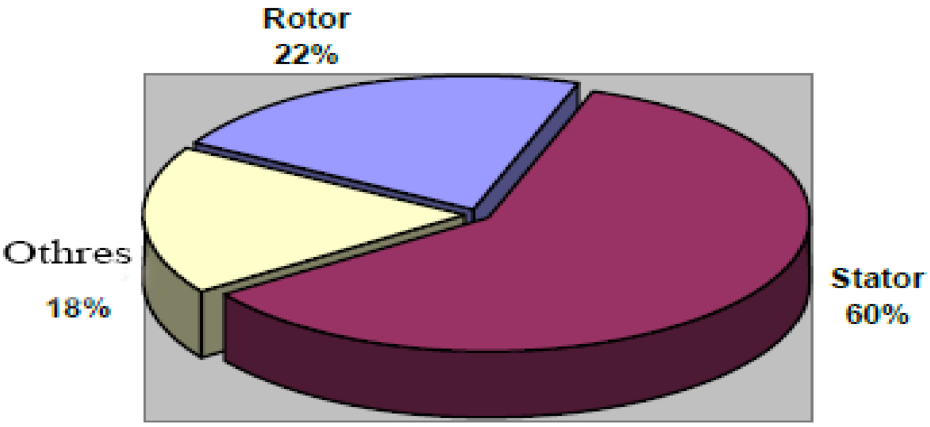


Fig I.6 Breakdown distribution [18]

Figure I.4 represents a statistical study that was carried out in 1988 by a German Industrial Systems Insurance Company on failures of medium-power induction machiness (from 50 Kw to 200 Kw)

I.3.2 Stator faults

According to Figure I.6, stator failures make up around 40% to 60% of the faults found in induction machiness that have various types. The main reason for stator faults is the deterioration of insulation. The stator winding in an electrical machine is subjected to a range of stresses from various factors, including thermal overload, mechanical vibrations, voltage spikes caused by frequency adjustments, and more [3].

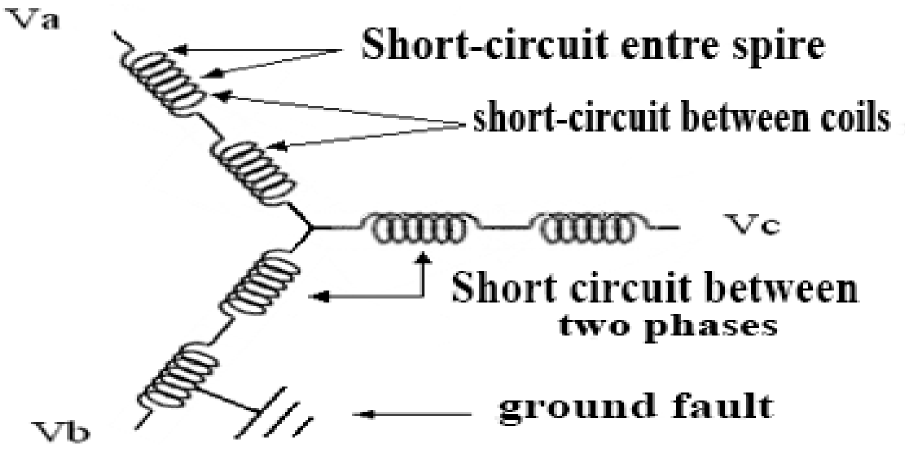


Fig I.7 Different types of stator faults

I.3.2.1 Insulation faults in a winding

The degradation of insulation in the windings can cause short circuits. This is because the various losses (Joule, iron, mechanical, etc.) generate thermal phenomena resulting in an increase in the temperature of the various components of the motor. However, insulation materials have limits in terms of temperature, voltage, and mechanical stress. Therefore, if the working environment of an insulation material exceeds one of these limits, the material degrades prematurely or accelerated, and eventually fails to perform its function. In this case, a short circuit may occur in the affected winding. The different causes for this type of fault are [6]:

- Deterioration of the insulation while being produced
- Exceeding the voltage limit of the insulation material when winding
- Elevated current within the winding caused by short circuits or overloading, resulting in premature deterioration of the insulation material due to a rise in temperature
- Vibrations caused by mechanical forces
- Normal wear and tear on the insulation over time
- Use in a challenging environmental setting [4].

I.3.2.2 Short-circuit between turns

A short-circuit between coils of the same phase is a fairly common fault. This failure originates from one or more insulation defects in the affected winding. It results in an increase in stator currents in the affected phase, a variation in amplitude in the other phases, alters the power factor and amplifies the currents in the rotor circuit. This causes a temperature rise in the winding, accelerating the deterioration of the insulation, which may lead to a chain fault (the appearance of a 2nd short-circuit). However, the average electromagnetic torque delivered by the machine remains essentially the same except for an increase in oscillations proportional to the fault.

I.3.2.3 Short-circuit between phases

This type of failure can occur anywhere in the winding, but the impact will not be the same depending on the location. This characteristic makes it difficult to analyze the impact of this fault on the system.

If a short circuit occurs close to the power supply between phases, it would induce very high currents that would lead to the melting of the power conductors and/or tripping of the protections. On the other hand, a short circuit close to the neutral between two phases causes an imbalance without causing the fusion of the conductors. The stator currents are totally unbalanced, and this imbalance is proportional to the fault that appears.

I.3.2.4 Magnetic circuit faults

These defects often result in asymmetry in the machine's operation, which can in turn exacerbate the problem through phenomena such as overheating, overvoltage, significant current increase, etc.

I.3.3 Rotor faults

The main causes of rotor failures can be attributed to various factors such as thermal, mechanical, electromechanical, residual, dynamic, and environmental phenomena. Specific examples of these faults include:

I.3.3.1 Bar breaks

In electrical machines, it is common for bars to break or rupture. This can happen either at the notch or at the end that connects to the rotor ring. When a bar is deformed, it causes changes in the electromechanical torque and speed oscillations, leading to mechanical vibrations. This indicates that there is a problem with the operation of the machine. There are several causes of bar breakage, including excessive vibrations, heavy loads, and contamination of the rotor material by environmental elements such as humidity and temperature etc.

I.3.3.2 Breakage of short-circuit rings

This issue is quite common, similar to bar breakages, and is caused by differential expansions between the bars and rings. Additionally, they carry currents that are greater than what the bars can support because they are short-circuited rings. Therefore, applying too much load will result in a high current demand, causing a portion of the ring to break and resulting in fluctuations in bar currents. This leads to the creation of modulations in the stator currents that are similar to those caused by bar breakages.

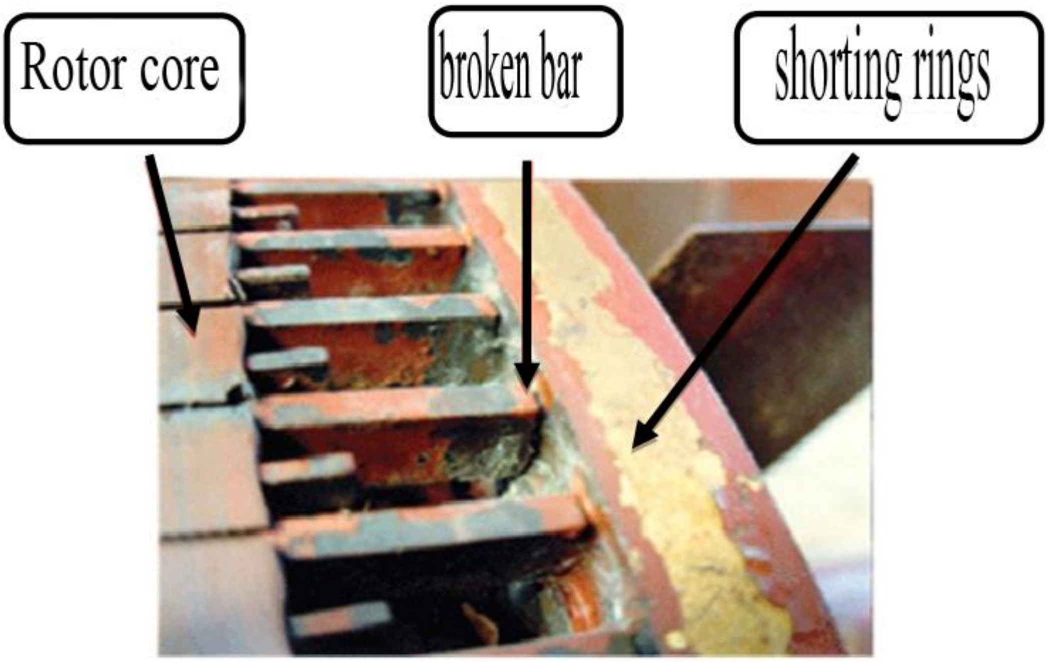


Fig **I.8** Example of a bar break fault of an asynchronous motor [19]

I.3.3.3 Static and dynamic eccentricity:

Rotor asymmetry, also referred to as dissymmetry, occurs when there is a lack of uniformity in the air gap. In some cases, the electric machine may suffer from rotor eccentricity, causing torque oscillations due to the offset between the shaft rotation center and the rotor center. This issue can arise from various factors such as motor shaft bending, improper rotor positioning, bearing wear, insufficient lubrication, or movement of the stator core.etc

The Three cases of eccentricity are generally distinguished as follows:

- Static eccentricity, where the rotor is displaced from the center of the stator bore but still rotates around its axis (the center of rotation of the rotor shaft is different from the geometric center of the machine).
- Dynamic eccentricity, where the rotor is positioned at the center of the stator bore but no longer rotates around its axis (the center of rotation of the rotor shaft rotates around the geometric center of the machine).
- Mixed eccentricity, which combines the two previously mentioned cases (it is the sum of the two previous cases).

One can represent static and dynamic eccentricity as follows:

Static eccentricity **Dynamic eccentricity**

Fig I.9 Schematic modeling of static and dynamic eccentricity [9]

The eccentricity causes variation in the air gap, leading to a non-uniform distribution of currents in the rotor and an imbalance of stator currents. In fact, an increase in eccentricity in the air gap induces an increase in electromagnetic forces that directly act on the stator core and its corresponding winding, leading to a degradation of its insulation. The resultant of radial magnetic forces (magnetic pull) becomes unbalanced. When this eccentricity increases, it can cause rotor-stator rubbing, damaging the magnetic circuit and stator winding. Additionally, this increase can result in friction between the stator and rotor due to magnetic attraction forces that unbalance the system [7], [8].

I.3.4. Mechanical failures:

I.3.4.1. Bearing faults

Bearings play the role of an electromechanical interface between the stator and the rotor. Additionally, they serve as the component that holds the machine's axis in place, ensuring proper rotation of the rotor ,this type of fault is the most common in high-powered machines. It is generally related to bearing wear, specifically the degradation of the balls or the tread. Possible causes include:

- Wear due to aging
- High operating temperature
- Loss of lubrication

- Contaminated oil (with metal flakes from the degradation of the balls or tread)
- Incorrect installation (Shaft currents)

The direct consequences of this failure on bearings are:

- Holes in the inner and outer bearing grooves
- Rippling of their rolling surface
- Surface peeling caused by overload On the system, this type of fault results in oscillations of the load torque, the appearance of additional losses, and play between the inner and outer bearing ring, leading to vibrations from the rotor movements around the longitudinal axis of the machine. In the worst case, the presence of a faulty bearing can lead to motor blockage [11].

I.3.4.2 Flange failure

In general, faults in the induction machines are primarily caused during the manufacturing process due to improper positioning of the end caps. Misalignment of the ball bearings as a result of the faulty position of the end caps can lead to eccentricity in the machine's shaft. One can detect this type of failure by performing a vibrational analysis or harmonic analysis of the currents absorbed by the machine [12].

I.3.4.3 Shaft failures:

he use of inferior materials during the construction of the machine's shaft can result in visible cracks that, over time, may cause a complete fracture of the shaft and an immediate shutdown of the machine. Additionally, corrosive environments like humidity can weaken the shaft and lead to complete machine destruction. Static, dynamic, or mixed eccentricity can also cause significant stress on the motor shaft and result in additional fatigue. To detect these types of failures, various types of analyses, such as vibrational, ultrasound, or frequency analyses, can be performed on the machine's shaft.

I.4 Fault Diagnosis Methods

I.4.1Vibration Analysis

Vibration analysis is a widely used method for detecting mechanical faults in induction machiness. The vibration signals generated by the machine can provide information about the condition of its components such as bearings, rotor, and stator. The frequency spectrum of the vibration signal can help identify the specific fault frequency related to a particular fault, such as bearing defects or unbalanced rotor. Vibration analysis can be carried out using various techniques, including frequency analysis, time-domain analysis, and wavelet analysis [52].

I.4.2 Current Signature Analysis

Current signature analysis (CSA) is a non-invasive method for detecting electrical faults in induction machiness. It involves analyzing the current waveform of the machine to identify any deviations from the normal operating condition. CSA can detect various faults, such as broken rotor bars, stator winding faults, and rotor eccentricity. The current waveform analysis is carried out using time-domain and frequency-domain techniques [13].

I.4.3 Motor Current Signature Analysis (MCSA)

Motor current signature analysis (MCSA) is a variant of current signature analysis specifically designed for asynchronous motors. It involves analyzing the current waveform of the motor to identify any deviations from the normal operating condition. MCSA can detect various faults, such as broken rotor bars, stator winding faults, and rotor eccentricity. The analysis is carried out using time-domain and frequency-domain techniques [39].

Fig I.10 Motor Current Signature Analyzer for Industrial [53]

I.4.4 Park's Vector

Analysis Park's vector analysis is a technique used to analyze the stator current and voltage signals of induction machiness. It involves transforming the signals from the time-domain to the rotating reference frame, where the analysis is carried out. Park's vector analysis can detect various faults, such as stator winding faults, broken rotor bars, and rotor eccentricity [38].

I.4.5 Neural Network-based Fault Diagnosis Neural network-based fault diagnosis

is an artificial intelligence-based approach used to diagnose faults in induction machiness. It involves training a neural network on a dataset of fault and non-fault data to classify the different types of faults. Neural network-based fault diagnosis can detect various faults, such as bearing defects, rotor faults, and stator winding faults [40].

I.4.6 Fuzzy Logic-based

Fault Diagnosis Fuzzy logic-based fault diagnosis is another artificial intelligence-based approach used to diagnose faults in induction machiness. It involves using fuzzy logic to model the uncertainties and imprecisions in the system and to classify the different types of faults. Fuzzy logic-based fault diagnosis can detect various faults, such as bearing defects, rotor faults, and stator winding faults [41].

I.4.7 Model-based Fault Diagnosis Model-based

fault diagnosis is a technique that involves building a mathematical model of the induction machines and using it to detect faults. The model is used to simulate the behavior of the machine under different operating conditions and to identify any deviations from the normal operating condition. Model-based fault diagnosis can detect various faults, such as stator winding faults, broken rotor bars, and rotor eccentricity [42].

I.5 Comparison of fault diagnosis method

Ref	Input signal	Signal processing	Validation	Proposed technique	Avantages
[20]	Therma	Thermal Images	Exp	Using feature vectors are obtained with the use MoASoID(method of areas selection of images differences and images histogram	Thermography is non-invasive and can be performed while the engine is running , making it easier to detect faults in real time
[21]	Current	FFT	Exp	Collect the data generated from the engine and convert it into a digital signal processing and artificial intelligence technologie	Diagnosis accuracy,diagnostic efficiency,multiple ese,low coste
[22]	Current	FFT	Sim	Analyze constant current signals using signal processing techniques such as fast fourier transform (FFT) and	It can improve engine reliability and prevent unexpected

				wavelet analysis	
[23]	Voltage current	measurement	Exp	This method involves using an observer to estimate the stator currents and voltages based on the measured values of the motor terminal currents and voltages	Improves engine relibility and safety
[24]	current	FFT	Exp sim	The 1D-LBP method is effective for stator fault detection in PMSM because it provides a high level of accuracy and is computationally efficient	Achieving high accuracy in fault detection
[26]	Current	FFT	Sim	It involves collecting vibration and deformation data and using diagnostic tools and techniques to determine the location and type of fault	Early detection of potential equipment failures allowing timely maintenance

[28]	Voltage Current	FFT	Sim Exp	This methodolgy involves analyzing the wavelet coefficient obtained from the current or vibration signals of the motor trough it the severity of stator faults can be determined	Early detection and maintenance before faults develop and cause more serious engine damage .
[29]	Voltage Current	FFT	Sim Exp	Use the extended kalman filter or unscented kalman filter to estimate the stator inter-turn fault Develop a mathematical model of the PMSG system and simulate it . Compare the simulation results with the actual system measurements to validate the filter accuracy	Improved accuracy and robustness in estimating fault parameters as well as reduced sensitivity to modeling errors and measurements noise
[30]	Voltage Current	FFT	Sim Exp	- Collect data on stator currents , voltages , speed - use signal processing technique to analyze the data and identify any abnormalities in the stator currents	The ability to detect faults in real time

Table I.1 : Comparison of fault diagnosis method

I.6 Conclusion

In this chapter, we have delved into statistical studies and the diagnostic techniques employed to analyze various aspects. Our primary focus revolved around the identification of the major failures that manifest in different components of the machine. We delved into the causes responsible for these failures and also explored their subsequent consequences. By conducting these studies, we aimed to gain a comprehensive understanding of the intricate mechanisms underlying the machine's operation. This knowledge allows us to devise effective strategies to mitigate the occurrence of failures and minimize their impact on overall performance. Moreover, the diagnostic techniques introduced in this chapter provide valuable insights into troubleshooting and maintenance procedures, enabling timely interventions and preventive measures. Overall, this chapter serves as a foundation for comprehending the intricacies of machine failures and equips us with the necessary tools to address and manage them efficiently.

Chapter II

Study of the time harmonics of the stator current

II.1 Introduction

The study of time harmonics in stator current is a crucial aspect of analyzing the electrical behavior of machines such as motors and generators. By examining the frequency content of the stator current waveform, we can identify the presence and characteristics of time harmonics, which are periodic components occurring at integer multiples of the fundamental frequency. This spectral analysis provides valuable insights into the condition and performance of the machine. By detecting and analyzing the harmonics, engineers and technicians can diagnose various issues such as unbalanced loads, faulty windings, core saturation, and power supply problems. This information aids in troubleshooting, maintenance, and optimizing the operation of the machines, ultimately ensuring their efficient and reliable functioning. Through a comprehensive study of the time harmonics in stator current, a deeper understanding of the machine's electrical behavior is attained, enabling informed decision-making and effective problem resolution.

II.2 General theory on the harmonics of the AM :

The air gap of an induction motor powered by a sinusoidal current is rich in various harmonics. Analysis shows that these harmonics of the air gap flux are due to interactions between the air gap permeance and the harmonics of the magnetomotive force (f.m.m.). It has been demonstrated that the rotor slot harmonics (**RSH**) are generated in the stator current line for a healthy machine at frequencies given by [32]:

$$_{1,2}(k) = \left|\left(h \pm \frac{kNr}{p}\;(1 - S)\right) fs\right| \qquad \text{(II.1)}\; f_{sh}$$

We notice that the mathematical expression (II.2) for the direct flux and (II.3) for the indirect flux clearly show that, in addition to the fundamental component, there are also a series of harmonics called rotor slot harmonics of order 'h' and at frequencies f_{sh} (p, Nr, k).

$$= \boldsymbol{L_{sc}I_{sd}} + \sum_{\mathbf{h \in G}}^{\infty} \frac{\mathbf{1}}{\mathbf{2}}\sqrt{\frac{\mathbf{3}}{\mathbf{2}}}\, \boldsymbol{N_r M_{srh} I_{rm}} \cos(\mathbf{2\pi f_{\mathit{sh}} t} \pm \boldsymbol{h}_{\boldsymbol{\varphi}\mathbf{h}} - \gamma) \quad \text{(II.2)}\boldsymbol{\varphi}_{\mathbf{sd}}$$

$$\boldsymbol{\varphi}_{\mathbf{sq}} = \boldsymbol{L_{sc}I_{sq}} - \sum_{\mathbf{h \in G}}^{\infty} \frac{\mathbf{1}}{\mathbf{2}}\sqrt{\frac{\mathbf{3}}{\mathbf{2}}}\, \boldsymbol{N_r M_{srh} I_{rm}} \sin(\mathbf{2\pi f_{\mathit{sh}}} \boldsymbol{t} \pm \boldsymbol{h}_{\boldsymbol{\varphi}\mathbf{h}} - \gamma) \qquad \text{(II.3)}$$

: *maximum rotor current value.*$\boldsymbol{I_{rm}}$

Also note that the derivative of the mathematical expression of the direct stator flux (II.2) shows that it will be zero except when 'h' belongs to the set 'G'. For this, only the **RSH** of order 'h', which belong to the set 'G', can be detected as such [33]

$$G=\{(h=1\ \cup h=(\frac{Nr}{p}\pm 1_{=1,2,3\dots})\cap\ h\ =\ (6v\pm 1)_{v=1,2,3}\}\qquad \text{(II.4)}$$

But in real cases, it is very difficult to find a perfectly balanced power source, even impossible, a well-centered winding as well as an ideally symmetrical geometry. Imbalance in voltages will lead to the creation of negative sequence currents (reverse field) in the stator windings, which give rise to other harmonic frequencies in the stator windings. This gives us, in the end, not only harmonics multiples of 3 but also odd ones such as: f_s, $3f_s$, $5f_s$, $9f_s$, ... We obtain harmonics whether the operation is healthy or faulty, such as [32]:

$$\mathbf{h} = |(2\mathbf{v}+\mathbf{1})|\ \mathbf{v=0,1,2,3\dots}\qquad \text{(II.5)}$$

In general, we have two sets of harmonics:

1- A set of time harmonics (**TH**) created by the non-asymmetry of the mmf with (k = 0) of characteristic frequencies [34], [35]:

$$(h) = hf_s \text{ou } TH = hf_s \qquad \text{(II.6)}\quad f_{TH}$$

2- A series of harmonics of rotor slots (**RSH**) with characteristic frequencies [32]:

$$\mathbf{S}^{\pm} = |(hf_s \pm KN_r f_r)|, \boldsymbol{f_{RSH}(h,k,s)} = |(h \pm \frac{\boldsymbol{KN_r}}{\boldsymbol{P}}(1-s)\,\boldsymbol{f_s}| \qquad \text{(II.7)}$$

With h=1,3,5,……

Thus, we can generalize our study in the same way as previously done for the natural manufacturing imbalance of the rotor, which results in a series of harmonics known as "Harmonics of Rotor Bar Fault" (**RBFH**) that resemble those of theoretical rotor bar breakage. Additionally, there are also the natural defects of static eccentricity and dynamic eccentricity, which result in mixed eccentricity. This also leads to a series of harmonics known as "Eccentricity Fault Harmonics" (**EFH**) [34], [35].

3-A series of harmonics of rotor bar faults (**RBFH**) with characteristic frequencies [35]:

$$(h, k, s)=|(h \pm 2ks)f_s| \text{ or } R_{\pm} = |(h \pm 2ks)f_s| \qquad \text{(II.8)}\boldsymbol{f}_{\mathbf{RBFH}}$$

4- A series of mixed eccentricity harmonics, called "Eccentricity Fault Harmonics" (**EFH**) with characteristic frequencies [32]

$$= |(h \pm \frac{\boldsymbol{KN_r}}{\boldsymbol{P}}(1 - s)\, f_s| \text{ or } \boldsymbol{E}^{\pm} = |(\,\mathbf{h}_{\boldsymbol{fs}} \pm \mathbf{kf}_{\boldsymbol{r}})\,| \qquad \textbf{(II.9)}\mathbf{f}_{\mathbf{EFH}(\mathbf{h},\mathbf{k},\mathbf{s})}$$

II.3 Study of the stator current with its harmonics:

We will focus our study on phase currents, as this work is essentially based on the analysis of existing harmonic spectra. Thus, we will replace the harmonics mentioned above (II.6) - (II.9) in the expressions given by the instantaneous currents flowing in the three phases "a", "b" and "c" of our asynchronous motor. These equations are given by (II.10) [34], [36]:

With

$I_{S^{\pm}K}$, $I_{R^{\pm}K}$,et $I_{E^{\pm}K}$ are respectively, they are the maximum phase current of supply for TH, RSH, RBFH, and EFH (amperes) (see Table II.1). Finally, **t** is the real time (in seconds). Here, m=1,3,5,7,9,... and n=1,2,3,4,...

$$\begin{cases} i_{sa}(t)_{\text{Healthy}} = \sum_{h=1}^{m} [\hat{I}_{THh} \sin(2\pi TH\, t) + \sum_{k=1}^{m} [I_{s\pm h} \cos(2\pi S^{\pm} t) + I_{R\pm K} \cos(2\pi R^{\pm} t) + I_{E\pm K} \cos(2\pi E^{\pm} t)]] \\ i_{sb}(t)_{\text{Healthy}} = \sum_{h=1}^{m} [\hat{I}_{THh} \cos(2\pi TH\, t - \frac{2\pi}{3}) + \sum_{k=1}^{m} [I_{s\pm h} \cos(2\pi S^{\pm} t - \frac{2\pi}{3}) + I_{R\pm K} \cos(2\pi R^{\pm} t - \frac{2\pi}{3}) + \\ \qquad I_{E\pm K} \cos(2\pi E^{\pm} t - \frac{2\pi}{3})]] \\ i_{sc}(t)_{\text{Healthy}} = \sum_{h=1}^{m} [\hat{I}_{THh} \cos(2\pi TH\, t - \frac{4\pi}{3}) + \sum_{k=1}^{m} [I_{s\pm h} \cos(2\pi S^{\pm} t - \frac{4\pi}{3}) + I_{R\pm K} \cos(2\pi R^{\pm} t - \frac{4\pi}{3}) + \\ \qquad I_{E\pm K} \cos(2\pi E^{\pm} t - \frac{4\pi}{3})]] \end{cases}$$

(II.10)

Types of harmonics	Their frequencies features	Their causes
Harmonics of time (TH)	$TH = hfs$	Imposed by the power source or symmetry of the
Notch harmonics rotors (RSH)	$S^{\pm} = \lvert (hf_s \pm N_r f_r) \rvert$	Caused by the structure of the rotor discrete distribution of) rotor bars (in the rotor slots
Fault harmonics of rotor bars (RBFH)	$R^{\pm} = \lvert (h \pm 2k_s) f_s \rvert$	Due to the asymmetry of the cage rotor rotoric
Fault harmonics of eccentricity (EFH)	$E^{\pm} = \lvert (hf_s \pm kf_r) \rvert$	Due to the natural mixed eccentricity of the rotor

.

Table.II.1 General expression of the different harmonics of the stator current [32]

The Park transformation is used to go from the three-phase system (a-b-c) to the two-phase system (d-q). The transformation expression is presented by [32]

$(\frac{\sqrt{2}}{\sqrt{3}})i_{sa}$ (t)- $(\frac{1}{\sqrt{6}})i_{sb}(t) - (\frac{1}{\sqrt{6}})i_{sc}(t)$ (II.11)$i_{sd} =$

$(\frac{1}{\sqrt{2}})i_{sb}$ (t)- $(\frac{1}{\sqrt{2}})i_{sc}(t)$ (II.12)$i_{sq} =$

In the ideal case, where there is only the fundamental harmonic, the Park vector currents $i_{sq}(t) et$ $i_{sd}(t)$ and in Eqs (II.11) and (II.12) can be simplified as follows [32]:

$= \frac{\sqrt{6}}{2} \hat{I}_{THh} \sin(2\pi fs\ t)$ (II.13)$i_{sd}(t)_{Healthy}$

$= \frac{\sqrt{6}}{2}\, \hat{I}_{THh} \cos(2\pi fs\, t)$ (II.14) $i_{sq}(t)_{Healthy}$

But in the real case of operation, where there is naturally the imbalance of voltages of the power source or the asymmetry of the winding, the asymmetry of the rotor of the rotor cage and the natural mixed eccentricity of the rotor, and after the replacement in Eq (II.13) and (II.14), we find the following expressions [32],[36].

$= \frac{\sqrt{6}}{2} \Big[\sum_{h=1}^{m} [\hat{I}_{THh} \sin(2\pi TH\, t) + \sum_{k=1}^{m} [I_{s\pm h} \sin(2\pi s^{\pm}\, t) + i_{sd}(t)_{Healthy}$

$I_{R\pm K} \cos(2\pi ER^{\pm}\, t) + I_{E\pm K}] \Big]\Big]$ (II.15)

$= \frac{\sqrt{6}}{2} \Big[\sum_{h=1}^{m} [\hat{I}_{THi} \cos(2\pi TH\, t) + \sum_{k=1}^{m} [I_{s\pm h} \cos(2\pi s^{\pm}\, t) + i_{sq}(t)_{Healthy}$

$I_{R\pm K} \cos(2\pi ER^{\pm}\, t) + I_{E\pm K} \cos(2\pi E^{\pm}\, t)]\Big]\Big]$

(II.16)

Remarke

This chapter will cover the analysis of the stator current's spectral characteristics, specifically focusing on its low and high frequency components and associated time harmonics. To accomplish this, we will utilize the Fast Fourier Transform (FFT).

II.4 Experimental example about time harmonics

We bring two identical induction motors used, in electric 3phase, 3 kW, 50 Hz, 2 poles, squirrel cage with 28 bar

At rotor and 360 turns respectively per phase:

1- healthy motor runs at full load (100%)

2- motor with stator faults runs at full load (100%)

with two cases

-short circuits between 5% of turns.

We measure the signal of the electric current with a special sensor connected to the computer to display the results [55] .

II.4.1 Case of a healthy machine

Figure II.1 shows the experimental spectrum of the stator current with its harmonics (healthy state). It is shown also how the evolution of time harmonics, their amplitudes and their specific frequencies which are multiples of 3 compared to the supply frequency with the healthy motor operating at no-load.

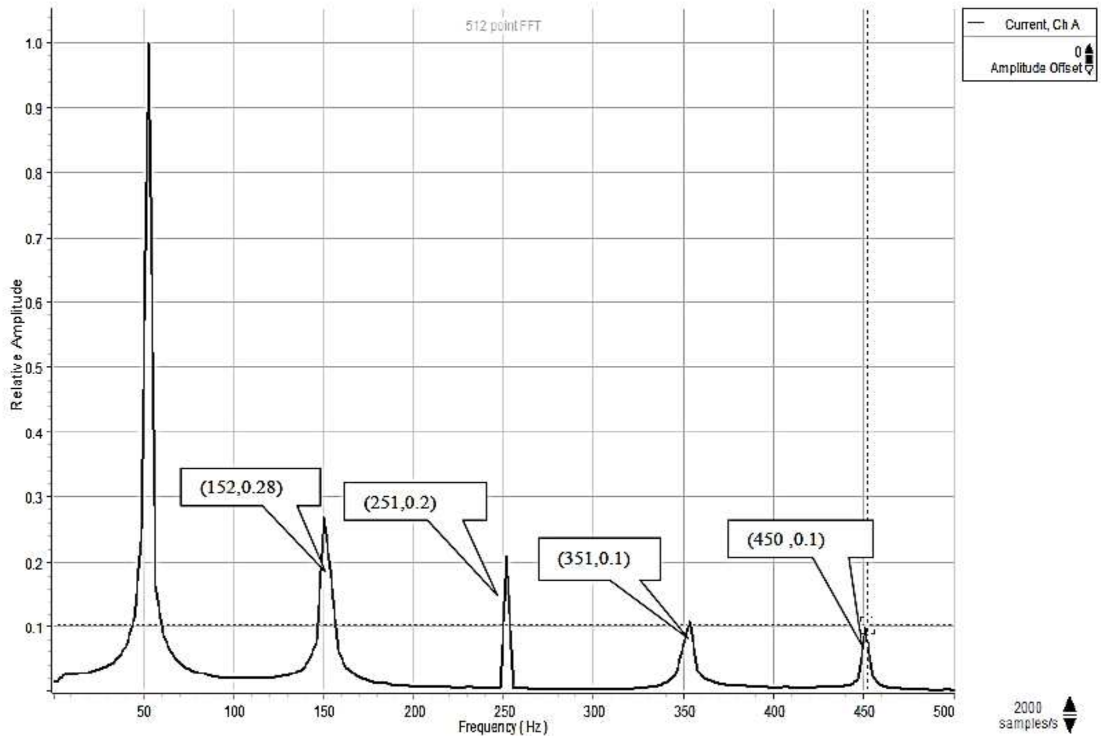


Fig II.1. Experimental spectrum of the stator current with its harmonics (healthy state).

Figure II.2 shows the evolution of the motor current in the time domain (2.7 Amperes) which is non-sinusoidal due to the imbalance of the motor and the non-symmetry of the materials of its manufacture

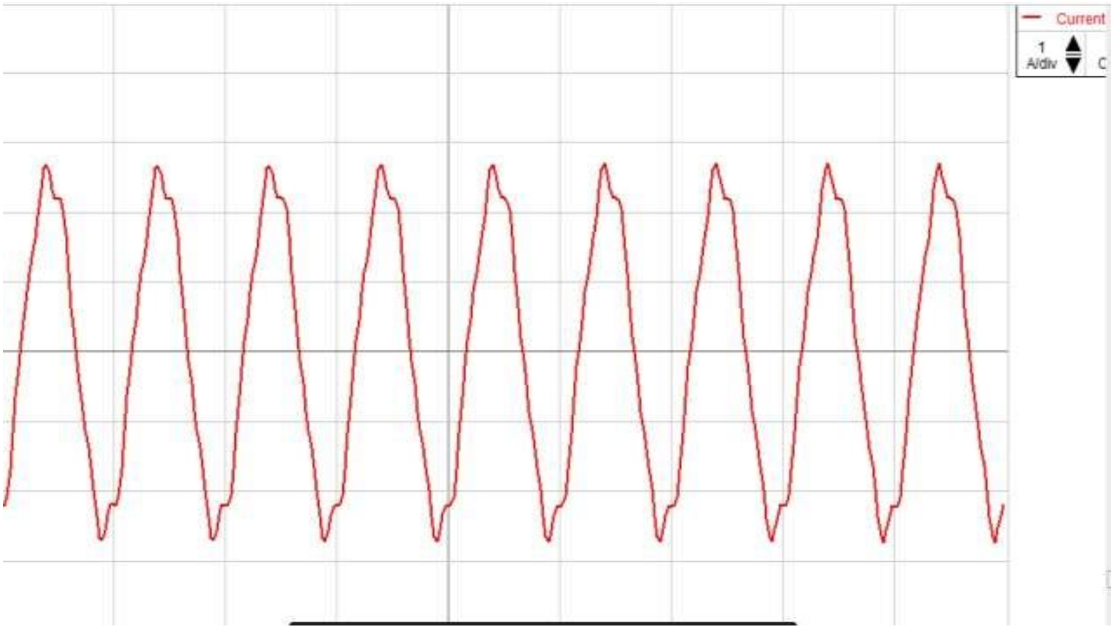


Fig II.2. Stator current healthy case.

II.4.2 Case of a machine with stator short-circuit

Figure II.3 shows the experimental FFT of the stator current with its time harmonics (with stator short-circuits 5% of turns). We notice the increase of time harmonics in the case of stator fault with 5 percent of turns in phase A

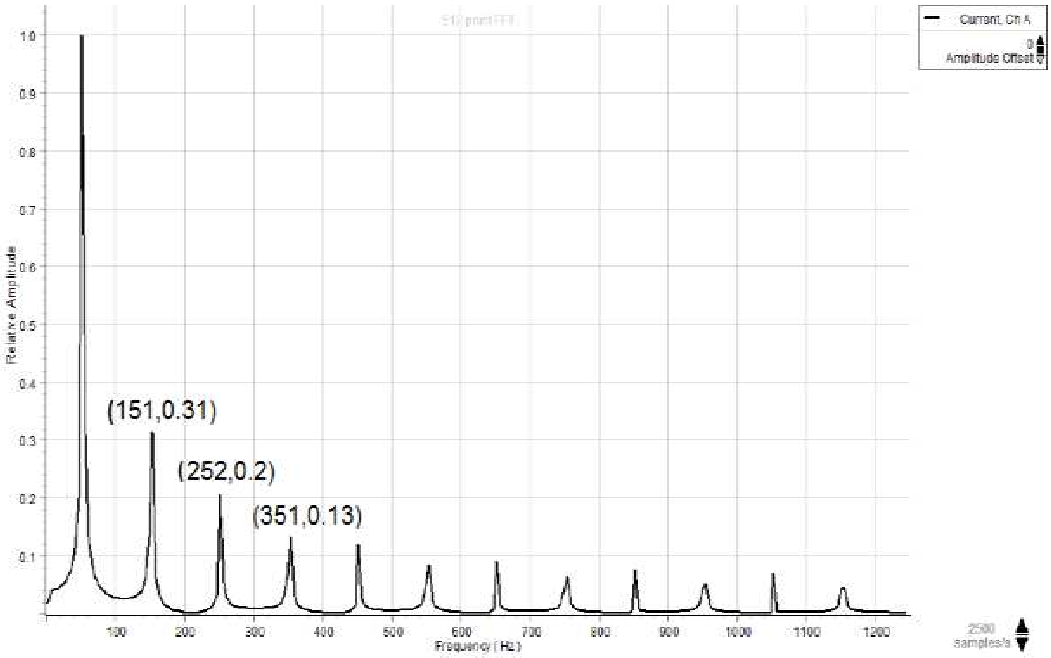


Fig II.3 Experimental FFT of the stator current with its time harmonics (with stator short-circuits 5% of turns)

Figure II.4 shows the evolution of the motor current in the time domain (3 Amperes) which further distorted the sinusoidal shape of the currents due to the stator fault.

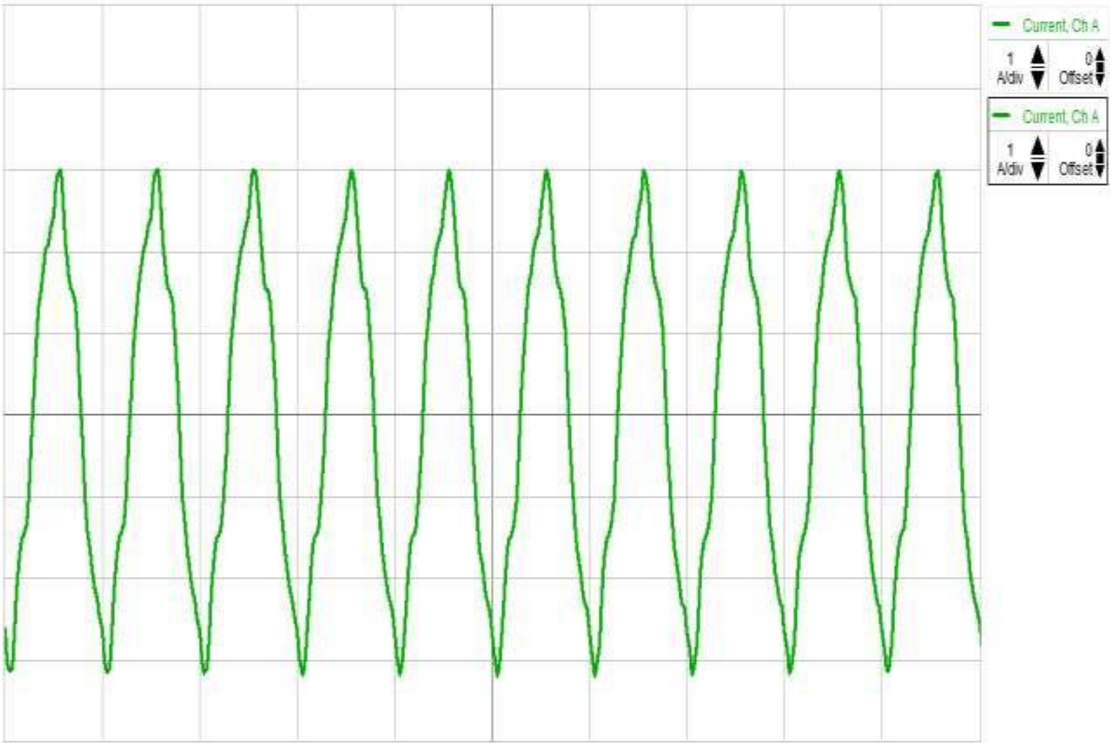


Fig II.4. Stator current faulty case.

II.6 Conclusion

The diagnosis of electrical machines witnessed a remarkable development in terms of diversity and modernity, so we tried to know the principles on which the diagnostic process is based, in addition to knowing the advanced modern diagnostic methods. Among them is the study of temporal harmonics, which was the subject of this chapter, to shed light on its advanced methods, with a theoretical narration for each of them, and an experimental example of that .

Chapter III

Spectral analysis of the stator current with the harmonics of the timeS

General conclusion

Due to their frequent use in various applications Induction machiness, necessitate prompt and early detection of potential faults to ensure their optimal performance. The focus of the presented work lies in the diagnosis of stator faults specifically in three-phase squirrel cage asynchronous motors.

To commence this study, we first revisited the range of faults that have the potential to impact the seamless operation of the squirrel cage three-phase induction machines, along with their underlying causes. By understanding the origins of these faults, we aimed to lay a foundation for effective diagnostic approaches.

Moreover, we conducted a comprehensive review of state-of-the-art monitoring techniques designed specifically for induction machiness. This review encompassed an exploration of various methods and strategies employed in the industry to monitor and assess the health and performance of these machines. By examining the advancements in monitoring techniques, we sought to identify and present the most effective and reliable approaches available.

After that, in the second chapter, we presented a method to study the diagnosis of induction machines with time harmonics. This method depends on studying the effect of the short circuit defect on the studied induction motor.

In the third chapter, we conducted an experimental study to gain a comprehensive understanding of the observations obtained from the simulation program (Pasco). This study allowed us to process the images of the current extracted from the current sensor and visualize the harmonic spectrum using a computer program.

The results obtained by these methods are considered satisfactory in relation to what was obtained It is found to this day by verification.

From this work we conclude that the sixth harmonic is more sensitive to fault detection stator

Our perspective is to study diagnosis with AI methods Such as: neural networks, genetic algorithm…

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Summary

Abstract

Diagnosing faults in the stator of induction machines plays a crucial role in ensuring reliable operation of electrical systems. Stator faults can lead to reduced motor efficiency, increased power consumption, and in some cases, complete motor failure. Therefore, accurate and effective detection and diagnosis of these faults are necessary to maintain motor performance, avoid equipment malfunctions, and prevent costly major repairs.

This work involves an experimental study of faults in induction machiness (with and without faults). After describing the main defects that can occur in these machines, we propose a method based on the harmonics of the stator current for fault diagnosis in induction machines. This technique is based on a study of the impact of an electrical short circuit on the motor, which has been investigated. We will identify the most affected harmonic component to be used as an indicator for diagnosing stator faults.

Keywords : motor, spectral analysis, stator fault, diagnosis, short circuit, time harmonics.

Résumé

Le diagnostic des défauts des parties fixes dans les machines asynchrones joue un rôle crucial dans la garantie du fonctionnement fiable des systèmes électriques. Les défauts des parties fixes entraînent une réduction de l'efficacité du moteur, une augmentation de la consommation d'énergie et, dans certains cas, une défaillance totale du moteur. Par conséquent, la détection et le diagnostic précis et efficace de ces défauts sont essentiels pour maintenir les performances du moteur, éviter les pannes d'équipement et prévenir les coûteuses réparations majeures. Cette étude consiste en une expérimentation sur les défauts des machines asynchrones (avec et sans défauts). Après avoir décrit les principaux défauts susceptibles de se produire dans ces machines, nous proposons une méthode basée sur les harmoniques du courant de la partie fixe des machines à induction. Cette technique repose sur une étude de l'effet d'un court-circuit électrique sur le moteur asynchrone, qui a été étudié, et nous identifierons le composant harmonique le plus affecté pour l'utiliser comme indicateur de diagnostic des défauts des parties fixes.

Mots clés : moteur à induction, analyse spectrale, défaut statorique, diagnostic, harmoniques temporels.

ملخص

يلعب تشخيص أعطال الجزء الثابت في الآلات الحثية دورًا مهمًا في ضمان التشغيل الموثوق للأنظمة الكهربائية ، تؤدي أعطال الجزء الثابت الى تقليل كفاءة المحرك ، وزيادة استهلاك الطاقة ، وفي بعض الحالات ، يؤدي إلى فشل المحرك بالكامل. لذلك ، فإن الكشف والتشخيص الدقيق والفعال لهذه الأعطال ضروري للحفاظ على أداء المحرك ، وتجنب أعطال المعدات ، ومنع أنظمة الإصلاح الرئيسية المكلفة. هذا العمل عبارة عن دراسة تجريبية لأعطال الآلات غير المتزامنة (مع وبدون أعطال). بعد وصف العيوب الرئيسية التي يمكن أن تحدث في هذه الآلات ، نقترح طريقة تعتمد على توافقيات تيار الجزء الثابت لآلات الحث ". وتستند هذه التقنية إلى دراسة تأثير ماس كهربائى على المحرك التعريفي تمت دراستها ، وسوف نحدد المكون التوافقي الأكثر تأثراً لاستخدامه كمؤشر لتشخيص أعطال الجزء الثابت.

كلمات مفتاحية : المحرك ، التحليل الطيفي ، خطأ الجزء الثابت ، التشخيص ، ماس كهربائى ، التوافقيات الزمنية

نحن الطلبة الاتية اسمائهم :حددعبد الرحمان ,صوالح محمد اسماعيل , الاطرش علاء الدين

نتنازل عن هذه النتائج الى المؤطر الدكتور علال عبد الرحيم ليستعملها في أعمال أخرى