

PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH



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Faculty of Technology
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Thesis submitted in partial fulfilment of the requirements for a
Master Degree in

Diagnosis of eccentricity faults in asynchronous motor by stator current harmonics

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Academic Year: 2023

APPRECIATION

In the beginning of this speech, we thank Almighty God for inspiring us with patience and strength and enabling us to complete this work. We would like to warmly thank our supervisor, **Dr. Alal Abdelrahim** and **Dr. khechekhouche abderrahmane** For their assistance, encouragement, and guidance in conducting our research work. We extend our sincere gratitude and appreciation to:

- All the members of the committee who honored us by evaluating our work.
- All the professors who contributed to our education during our academic years.

ملخص

هذا العمل يدرس أهمية تشخيص المحركات الغير متزامنة باستخدام الترددات الطيفية لتحديد عيوب غرابة الدوران في العضو الدوار. تستخدم الدراسة مقاييس تجريبية مع أحمال متغيرة بناءً على التردد الزمني للعثور على التردد الأكثر حساسية لتشخيص هذا النوع من العيوب من خلال تحليله باستخدام تقنيات التحليل الطيفي. وقد سمح هذا العمل لنا بالعثور على التردد الأكثر حساسية للكشف عن العيب في مرحلة مبكرة، مما يساعدنا على تجنب حدوث أضرار مادية هائلة أو أذى بالجسم، خاصة في القطاعات الصناعية مثل الكيمياء أو الطاقة النووية

. **كلمات مفتاحية:** المحركات الغير متزامنة دات القفص ، خطأ الدوار، تشخيص، المراقبة، الكشف،

نموذج متعدد اللغات

Abstract

This work studies the importance of diagnosing asynchronous machines using stator current harmonics to identify rotor eccentricity faults. The study uses an experimental test bench with variable loads based on time harmonic to find which harmonic is most sensitive for diagnosing this type of fault by analyzing it using spectral analysis techniques. This work allowed us to find the most sensitive harmonic order for detecting the fault at an early stage, which helps us avoid huge material damage or bodily harm, especially in industrial sectors such as chemistry or nuclear.

Keywords: cage asynchronous motors, rotor fault, diagnosis, monitoring, detection,

Résumé

Ce travail étudie l'importance du diagnostic des machines asynchrones en utilisant les harmoniques du courant statorique pour l'identification des défauts d'excentricité du rotor. Cette étude utilise du banc d'essai expérimental avec des charges variables en se basant sur l'harmonique de temps pour trouver quels

harmonique le plus sensible pour le diagnostic de ce type de défaut en l'analysant à l'aide de techniques d'analyse spectrale. Ce travail nous a permis de trouver l'ordre de l'harmonique le plus sensible pour découvrir le défauts à un stade précoce ce qui nous évite des dégâts matériels énormes ou des pertes corporelles surtout dans les secteurs industriels de la chimie ou de la nuclear

Mots clés : moteurs asynchrones à cage, défaut rotor, diagnostic, surveillance, détection,

NOTATION AND SYMBOLS

N_s: number of stator turns per phase

Ω_s : synchronous speed

F_s : power supply frequency

p: number of pole pairs

g : slip

Ω : rotor speed

AM : asynchronous machine

f.m.m : the magnetomotive force

I_{rm} : maximum rotor current value

RSH : rotor slot harmonics

TH : time harmonics

RBFH : Harmonics of Rotor Bar Fault

EFH : Eccentricity Fault Harmonics .

I_{rk}: current in the rotor loop

N_r: number of rotor bars.

I_a, I_b, I_c: stator phase currents

φ_s: magnetic flux per pole created by the stator current

φ_{abc}: stator fluxes [wb]

V_{abc}: stator voltages [V].

FFT: Fast Fourier Transform

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General Introduction

General Introduction

This work focuses on diagnosing faults in electrical machines, specifically in squirrel-cage asynchronous motors, which are a critical component in most industrial equipment. While squirrel-cage asynchronous motors are known to be the most robust type of electrical machine, several factors of different natures (thermal, electrical, mechanical, and environmental) can affect their lifespan and cause faults in the stator and rotor, resulting in significant economic losses.

To overcome this issue, this work aims to develop advanced diagnostic techniques to detect faults early in squirrel-cage asynchronous motors, utilizing spectral analysis to analyze the frequency components of the stator current and identify rotor faults.

This work consists of three chapters, with the first chapter discussing the possible causes and types of faults in squirrel-cage asynchronous motors different diagnostic methods that can be used to detect these faults , while the second chapter presents The diagnosis using the harmonics of the stator current for detecting rotor eccentricity faults.. The third chapter includes a experimental results, focusing on spectral frequency analysis of the harmonic stator current and the application to detect rotor faults. We used the time harmonic for the identification of this type of fault. Our study discovered the time harmonic order that is most sensitive for the diagnosis of rotor faults with varying loads.This work emphasizes the importance of developing advanced diagnostic techniques to ensure preventive monitoring and maintenance of squirrel-cage asynchronous motors, which can help detect faults early and prevent unexpected downtime, contributing to the improvement of production quality and profitability of industrial equipment. To achieve this, it is necessary to focus on providing the necessary knowledge about electrical machines and possible faults, as well as

expertise in spectral analysis. Further research is needed to improve these diagnostic techniques and apply them to other types of electrical machines.

Overall, this study provides an opportunity to improve the understanding of the causes of faults in squirrel-cage asynchronous motors and the different diagnostic methods necessary for early detection of these faults. By developing advanced diagnostic techniques, the performance of squirrel-cage asynchronous motors can be improved, reducing faults and unexpected downtime, and ultimately enhancing the productivity and profitability of industrial equipment. To achieve this, the necessary knowledge and expertise in spectral analysis must be provided. Further research and development are required to improve these diagnostic techniques and apply them to other types of electrical machines. This work represents an important contribution to the field of electrical engineering and can help improve the efficiency of vital industrial equipment.

Chapter I

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I.1.Introduction:

Due to its low cost, small size, high efficiency, and excellent reliability, the asynchronous motor is widely used in various industrial applications. This chapter aims to provide a basic understanding of diagnostic activities related to asynchronous motors. It begins by exploring the different components of the squirrel-cage induction motor, followed by a discussion of the various faults that can affect these components. The chapter concludes by introducing different methods used for detecting faults in induction motor.

I.2. Constitution of the induction motor

The induction motor, often called the induction motor, consists of a stator and a rotor made up of silicon steel sheets and having slots in which the windings are placed. The stator is fixed and contains the windings connected to the power source. The rotor is mobile and is mounted on a rotating axis. Depending on whether the rotor windings are accessible from the outside or are permanently closed on themselves, two types of rotors are defined: wound or squirrel-cage [6]. In this section, we propose to provide some information on the constituent elements of induction motors. This description will allow us to understand how the system is physically realized. Three-phase induction motors can be mechanically decomposed into three distinct parts, as shown in Fig(I.1):

- the stator, the fixed part of the machine where the power supply is connected
- the rotor, the rotating part that allows the mechanical load to be rotated
- the bearings, mechanical parts housing the bearings and supporting the rotor via the shaft.

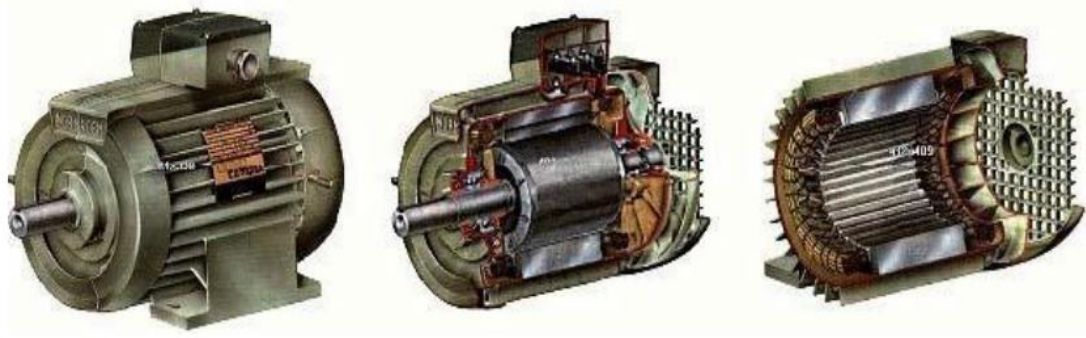


Figure (I.1): Structure of the asynchronous squirrel-cage machine [2].

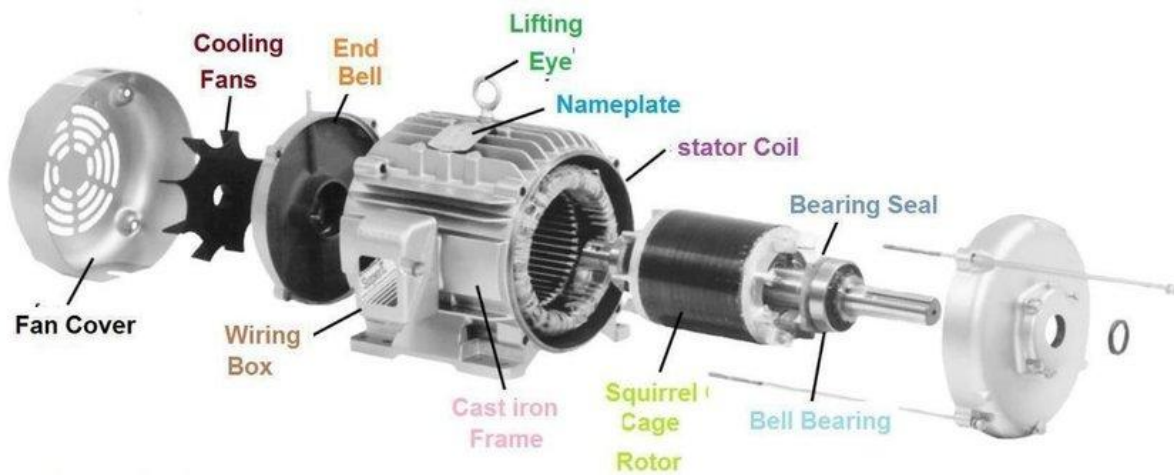


Figure (I.2): Different components of the squirrel-cage induction motor

I.2.1. The stator

The magnetic circuit is a stack of thin steel sheets on which the stator slots housing the winding conductors are cut. Thin sheets with a thickness ranging from 0.35 mm to 0.50 mm are used to minimize iron losses in the magnetic circuit (Fig I.2). In addition, to limit the effect of eddy currents, the sheets are usually insulated from each other with a thin layer of varnish or sodium silicate. The stator winding consists of two parts: the slot conductors and the coil heads (Fig I.3). The slot conductors create the magnetic field in the air gap that is responsible for the conversion of electromagnetic energy. The coil heads, on the other hand, allow the current to flow by organizing their circulation [2].

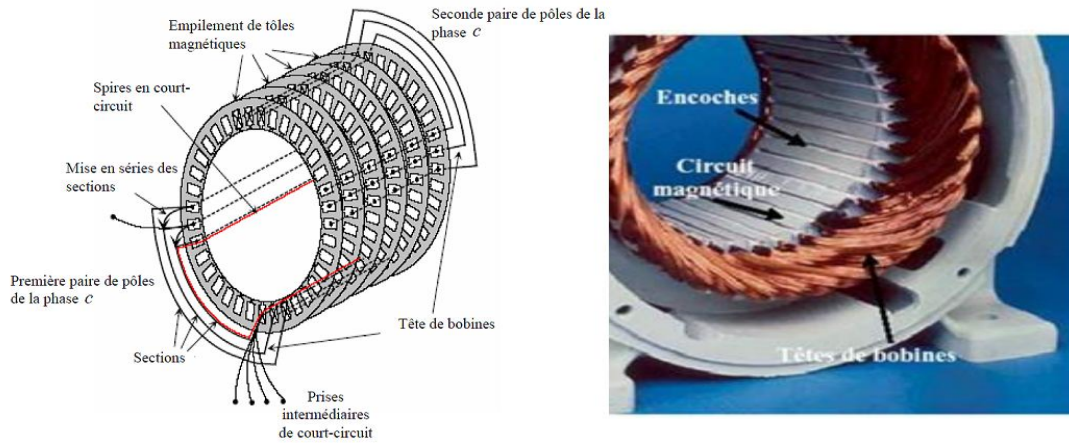


Figure (I.3): Schematic cutaway of the stator's composition[26].

The objective is to obtain a sinusoidal distribution of the magnetomotive forces at the air gap in order to limit electromagnetic torque ripples. Stator windings can be executed in several ways. Usually, three types of windings are used: the lap winding, the concentric winding, and the wave winding. Each type of winding has advantages for certain applications. For low-power motors, especially when winding production is mechanized, the concentric winding is generally used.

I.2.2. The rotor

The rotor is made of stacked laminations, usually of the same material as the stator. In small motors, the laminations are cut from a single piece and assembled on a shaft. In larger motors, each lamination is made up of several sections mounted on a hub. In the squirrel-cage rotor, the conductors are bars made by injecting an aluminum alloy or pre-formed copper and inserted into the rotor laminations. There is usually little or no insulation between the rotor bars and the magnetic laminations, but their resistance is strong enough that currents do not flow through the laminations, except when there is a bar breakage. There are two types of rotor: wound or squirrel-cage.

I.2.2. 1. Wound Rotor

The rotor windings are located in the slots located at the periphery of the rotor. These windings are wound to obtain a three-phase winding with "p" pole pairs. The rotor windings are always connected in a star, and the three accessible terminals are connected to the stator frame using a system consisting of three rotating rings and three fixed brushes.

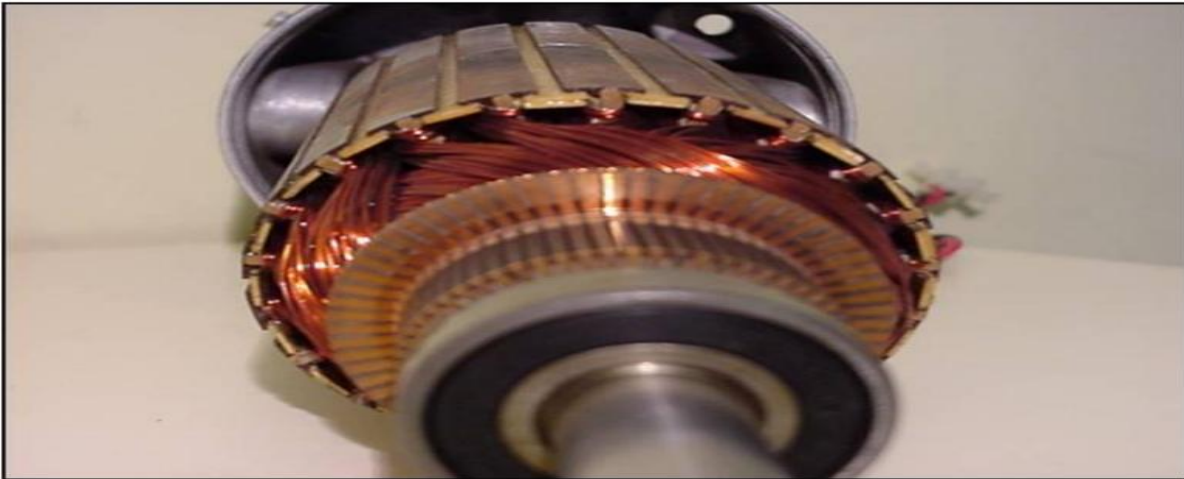


Figure (I.4): Wound rotor of an induction motor [26].

I.2.2. 2. Squirrel-cage rotor:

The vast majority of motors use squirrel-cage rotors. In each rotor slot, a bar is placed. These bars are made of copper for high-power motors and aluminum alloy for low and medium power machines. They are connected at each end of the rotor by rings that short-circuit them. The resulting rotor winding is not accessible from the stator [4],[5].

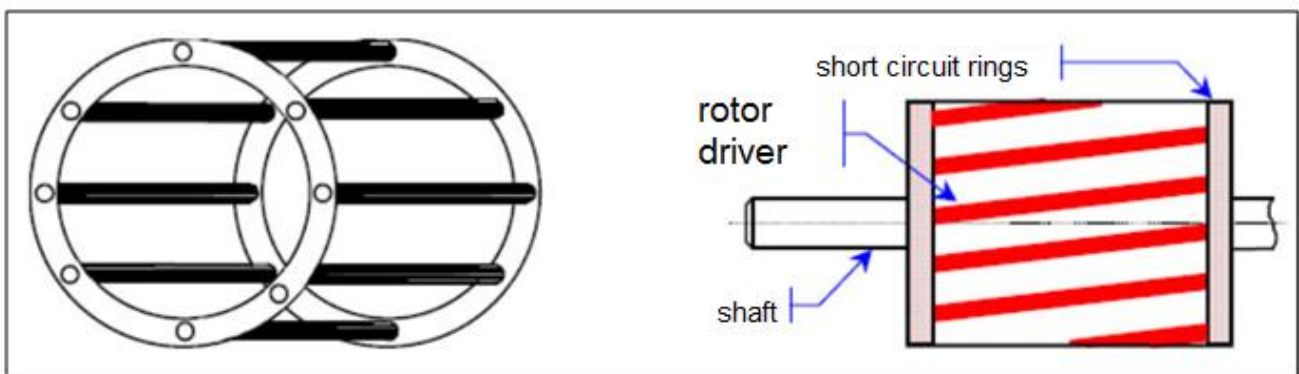


Figure (I.5): Schematic cutaway for the construction of the rotor [27].

I.2.3. Bearings:

The bearings support the rotor and ensure its free rotation. They consist of the flanges and ball bearings. The cast iron flanges are fixed to the stator housing, providing support and centering of the outer rings of the ball bearings. The bearings, which are inserted hot on the shaft, ensure the rotational guidance of the rotor [3].

I.3. Operating principle of an induction motor:

The operating principle of an asynchronous motor is based on the induction of an electric current in a conductor placed in a rotating magnetic field. The conductor in question is one of the bars of the squirrel-cage rotor. The induction of the current can only occur if the conductor is short-circuited (which is the case since the two lateral rings connect all the bars). In addition, a driving force is created on the conductor (which is traversed by a current and placed in a rotating or variable magnetic field) whose direction is given by the right-hand rule [6].

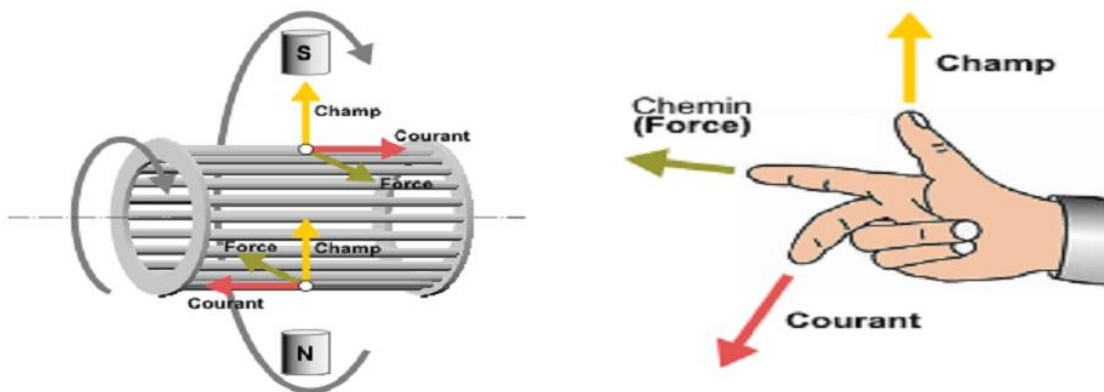


Figure (I.6): Simplified operating principle of an asynchronous motor [27].

In this way, the operation of an induction motor is analogous to that of a transformer: the stator being comparable to the primary winding and the rotor to the secondary winding, which in general can rotate at a speed given by the following ratio:

$$n_1 = \frac{f_s}{p} \quad (\text{I.1})$$

where f_s : represents the frequency of the stator current and p : the number of pole pairs. The electromagnetic interaction of the two parts of an induction motor (without a commutator) is only possible when the speed of the rotating field (n_s) differs from that of the rotor (n), that is, when $n \neq n_s$, because otherwise, when ($n = n_s$), the field would be stationary relative to the rotor and no current would be induced in the rotor winding. The ratio :

g : is called the slip of an induction motor [4].

I.4. Failures of the squirrel-cage induction machine:

Although the squirrel-cage induction machine is known for its robustness, it may sometimes exhibit different types of faults. These faults can be of electrical or mechanical origin. A minor problem during the manufacturing stage may be the cause of a fault, as well as non-compliant use of the machine. Sometimes, the environment in which the machine is used (corrosive and/or hostile chemical environments) can also be to blame.

I.5. Electrical Failures:

Electrical failures may, in some cases, be the cause of machine shutdown (similar to mechanical failures). These failures are divided into two distinct categories: those that occur at the stator electrical circuits level and those that occur at the rotor electrical circuits level [1].

I.5.1. Failures in stator electrical circuits

The appearance of a fault in the stator electrical circuits of the induction motor can have various origins. For example, inter-turn short-circuit faults that appear inside the stator slots can be caused by degradation of the insulation of the stator winding coils. There are also short-circuits that occur between a phase and the neutral, between a

phase and the metal frame of the machine, or between two stator phases. These faults are most often of mechanical origin. Excessive vibrations can lead to loosening of the bolts of the machine's terminal plate, thus creating a short circuit. A poorly tightened connector at the junction of the power cable and the machine's terminals can cause a phase opening. The most commonly encountered fault remains the fusion of a protective fuse. These faults can be detected by a harmonic analysis of the currents absorbed by the machine [7][9][8].

I.5.2. Failures in rotor electrical circuits

I.5.2.1. Breakage of rotor bars

These faults appear at the rotor level and are the most frequent. They are characterized by total or partial breaks of one or more bars in the squirrel-cage (e.g. Figure I.6 with a broken bar rotor). These faults result in an increase in the equivalent resistance of a rotor winding. These rotor failures unfortunately generate electromagnetic torque ripples, which in turn cause oscillations in the machine's rotational speed, leading to additional mechanical faults in the machine.

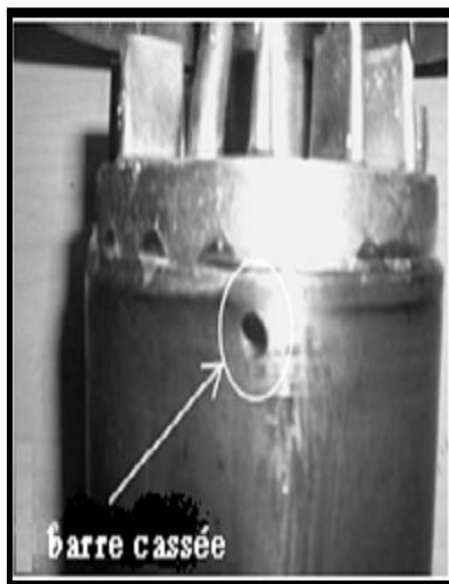


Figure (I.7): Fault of a broken bar [2].

I. 5.2.2. Breakage of a portion of the short-circuit ring

Breakage of portions of the short-circuit ring is due either to casting bubbles or to expansions between the bars and the rings (e.g. Figure I.7 with a broken short-circuit ring). The short-circuit rings carry higher currents than the rotor bars. Inadequate sizing of the rings, deterioration of operating conditions, or overload of torque and therefore current can lead to their breakage. The breakage of a portion of the short-circuit ring results in behavior similar to that of broken bars.

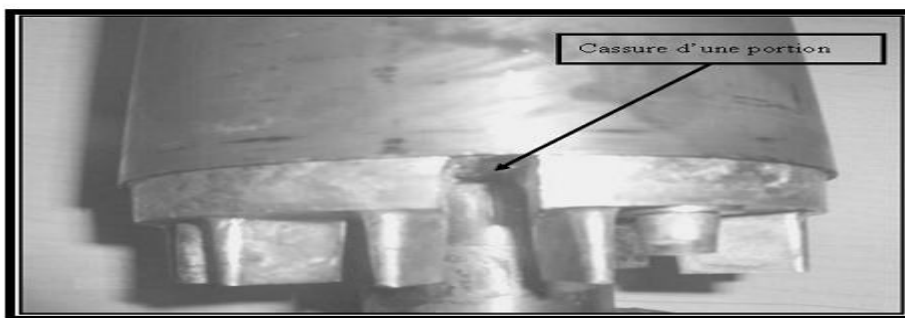


Figure (I.8): Breakage of a portion of the short-circuit ring

Suite to the appearance of these faults, the machine continues to function, and it is therefore difficult to detect these failures. The current carried by a broken bar is distributed among the other bars, which become overloaded and can lead to their breakage and subsequently to the breakage of a larger number of bars [9].

I.5.3. Mechanical failures:

Mechanical failures are generally the most encountered among all the faults of the induction motor. These faults can occur at the ball bearings, flanges, or motor shaft. In the rest of our paper, we list some of these faults. Comprehensive works dealing with these various problems can be found in the literature [10][11].

I.5.3.1. Ball bearing faults:

Ball bearings play a very important role in the operation of any type of electrical machinery. Bearing faults can be caused by poor material selection during the

manufacturing stage. Problems with rotation within the bearings, vibrations, and high temperatures can lead to bearing wear, fatigue, and ultimately, failure. The use of contaminated lubricants or insufficient lubrication can also lead to bearing failures.

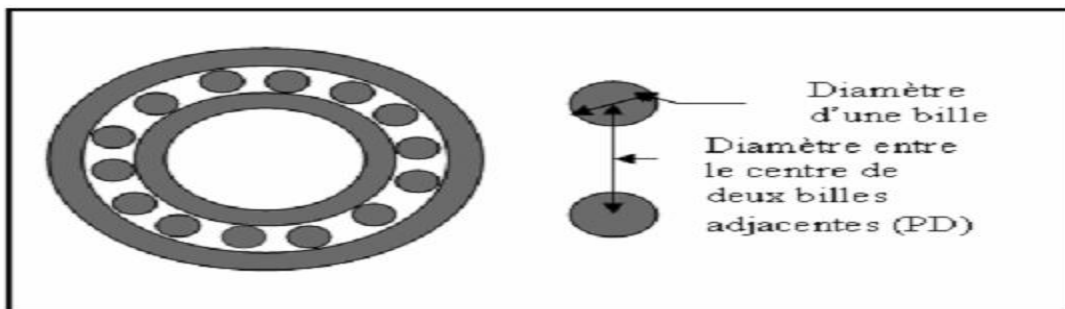
Bearing faults caused by damaged, chipped, or cracked winding can create disturbances within the machine. We know that electrical currents flow in the bearings of an induction motor, which, for high speeds, can cause their deterioration. Grease, which allows for lubrication and proper rotation of the bearings, can in some applications stiffen and cause resistance to rotation [12]. Bearing faults manifest as asymmetry faults in the rotor, which are usually classified as eccentricity faults. A bearing fault is manifested by the continuous distribution of the defective contact with the outer bearing cage and the inner bearing.

The relationship between ball bearing vibrations and the stator current spectrum is based on the fact that all eccentricities interfere with the field in the air gap of the induction motor. Therefore, the harmonics contained in the stator current spectrum can be described by the following expressions [13]:

$$f_{exe} = \left(1 \pm k \left(\frac{1-s}{p/2} \right) \right) f \quad (\text{Hz}) \quad v \quad (\text{I.2})$$

$$f_{exe} = |f \pm k \cdot f_{rm}| \quad (\text{Hz}) \quad f_{bng} = |f \pm m \cdot f_{vib}| \quad (\text{Hz}) \quad (\text{I.3})$$

Where f_{vib} is one of the frequencies of mechanical vibrations.



Figure(I.9): Ball bearings [21].

where s represents slip, f is the supply frequency, and f_{rm} is the mechanical rotation frequency, $m = 1, 2, 3, \dots$; $n \in \mathbb{N}$, $k = 1, 3, 5, \dots$; $k \in \mathbb{N}$, p is the number of pole pairs, n_b is the number of balls; D_b is the ball diameter, D_c is the distance from the center of the balls, and θ represents the contact angle of the ball with the cage.

The different types of faults in ball bearings are represented in Figure (I.9).

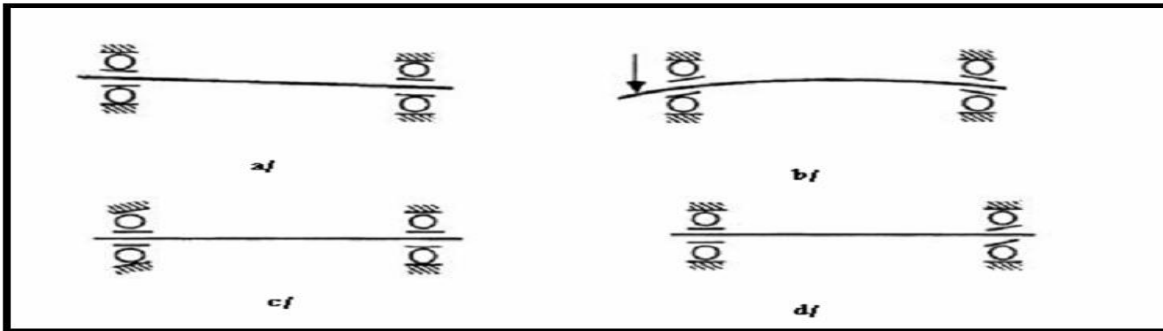


Figure (I.10): Four types of faults in ball bearings [21].

a/ Misalignment; **b/** Deformation of the rotating shaft;

c/ Tilt of the outer race; **d/** Tilt of the inner race.

I.5.3.2. Eccentricity

Variations in the air gap width lead to variations in the air gap flux density. The stator windings are electrically affected, and these effects can be seen in the current spectrum. Generally, three types of eccentricity can be distinguished [4]. (Figure I.10) shows the different types of eccentricity:

- Static eccentricity, where the rotor is displaced from the center of the stator bore but still rotates around its axis;
- Dynamic eccentricity, where the rotor is positioned at the center of the bore but no longer rotates around its axis;
- Mixed eccentricity, which combines the two previously mentioned cases.

Static and dynamic eccentricity can be represented as follows (Figure I.10):

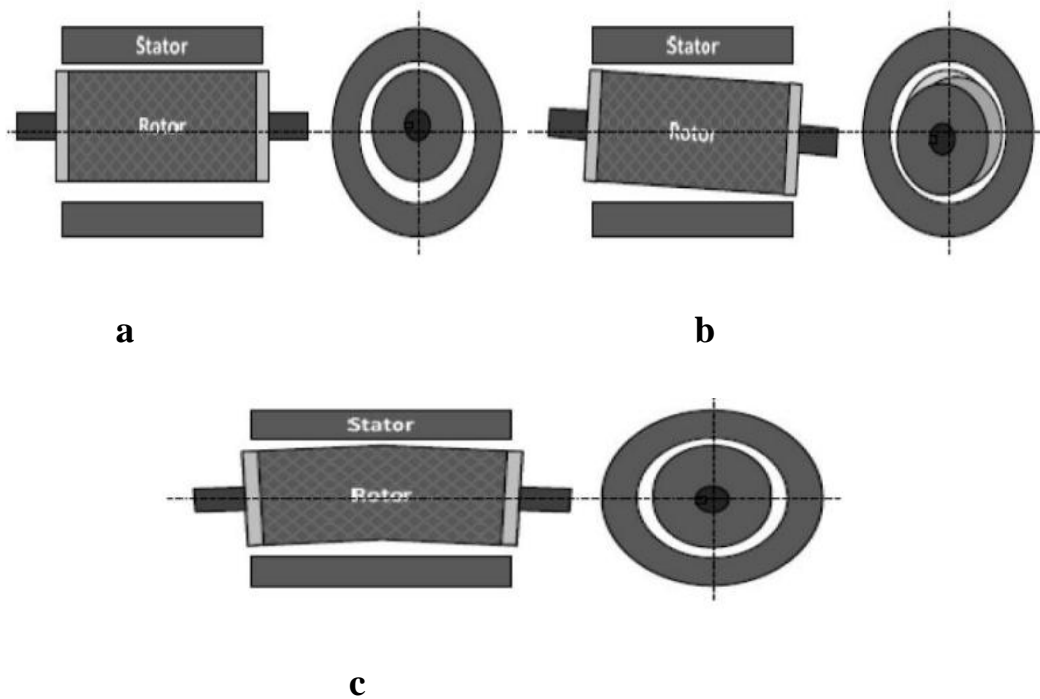


Figure (I.11): Eccentricity faults [2].

a/ Static eccentricity, b/ Dynamic eccentricity, c/ Mixed eccentricity.

I.5.3.3. Shaft failure

The machine shaft may exhibit a crack due to the use of improper material during construction. In the short or long term, this crack can lead to a clear fracture of the shaft, resulting in the irreparable stopping of the induction motor. Corrosive environments can also weaken the robustness of the shaft. For example, moisture can cause micro-cracks and lead to complete destruction of the machine. Static, dynamic, or mixed eccentricity can induce considerable stress on the motor shaft, leading to additional fatigue. Vibrational analysis, ultrasound analysis, frequency analysis of absorbed currents, or simply visual analysis of the machine shaft can be used to detect this type of failure [6].

I.5.3.4. Flange failure

Defects caused by the flanges of the induction motor are generally caused during the manufacturing stage. Improper positioning of the flanges can cause misalignment. This

type of defect can be detected by vibrational analysis or harmonic analysis of the currents absorbed by the machine [14].

I.6. Causes of failures

The causes of faults are multiple and can be classified into three groups: fault initiators, fault amplifiers, and manufacturing defects [15]. The majority of rotor and stator faults are caused by a combination of various forces acting on these two components of the machine.

I.6.1. Causes of stator faults

Stator faults can be caused by several reasons, including [16], [15]:

- A large stator core where the winding temperature is high;
- Loose attachment at the end of the winding;
- Contamination due to oil, mold, or dirt;
- Frequent starting cycles;
- Overvoltage, electrical discharges, and leaks in cooling systems.

I.6.2. Causes of rotor faults

Like the stator, there are several reasons for the breakage of rotor bars and the rupture of a portion of the short-circuit ring:

- Thermal stress due to the heating of the short-circuit ring and the temperature difference in the bar during startup (skin effect);
- Magnetic stress caused by electromagnetic forces (slot leakage flux, air gap eccentricity), electromagnetic noise, and vibrations;
- Dynamic stress due to the load torque, centrifugal forces, and cyclic stresses;
- Environmental stress caused by contamination, abrasion of rotor materials due to chemical particles.

I.6.3. Causes of ball bearing faults

Even under normal operating conditions with balanced load and proper alignment, fatigue-related faults, apart from those due to normal internal operation inherent to eccentricity, can occur. Other external causes may also exist, such as:

- Contamination and corrosion caused by water and acid...
- Improper lubrication.
- Improper bearing installation due to machine misalignment.

I.7. Methods of fault detection in three-phase asynchronous cage motors

In order to properly classify our work, it is very important to have a general idea of the different methods used for diagnosing anomalies in electrical machines. Knowing that several works have focused on this area for a long time, there are therefore several approaches and techniques that have been widely studied [21] [3] It is important to note that the different diagnostic methods are classified according to the approaches they belong to. In fact, there are two approaches: Signal Approach and Model Approach.

I.7.1. Fault diagnostic methods based on spectral analysis of signals

To diagnose an industrial installation, maintenance operators analyze a number of signals from the machine. Indeed, the temporal evolution and spectral content of these signals can be exploited to detect and locate anomalies that affect the proper functioning of the machine. According to the literature, the main diagnostic techniques used to obtain information about the health status of the machine are as follows:

I.7.1.1. Diagnosis by mechanical vibration analysis

Diagnosing faults using mechanical vibrations is the most commonly used method in practice. The radial forces created by the air gap field cause vibrations in the induction motor. These forces are proportional to the square of the magnetic induction [22] [3].

$$\sigma(\theta, t) = \frac{B_s^2(\theta, t)}{2\mu_0} \quad (\text{I.4})$$

The distribution of magnetic induction in the air gap is the product of the magnetic field and permeance (P).

$$B = p \cdot F_m \quad (\text{I.5})$$

The machine vibrations can be captured by accelerometers placed on the bearings in the axial, vertical, and radial directions. The spectra of the vibration signals from the faulty motor are compared with those of references recorded when the motor was in good condition. This method allows for the detection and diagnosis of mechanical faults such as unbalance, misalignment, and bearing defects.

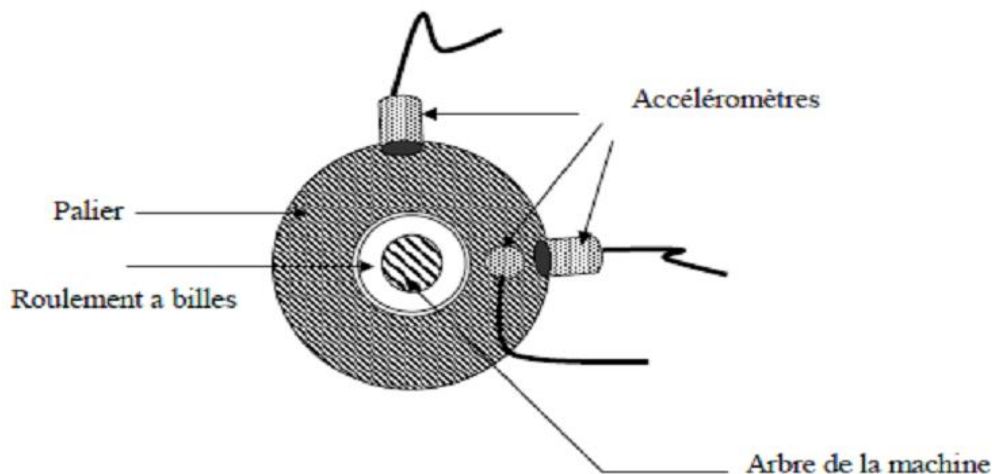


Figure (I.12): Vibrational measurement of the three-phase asynchronous motor[26]. .

I.7.1.2. Diagnosis by analysis of the axial magnetic leakage flux

The presence of any fault causes an electrical and magnetic imbalance in the stator and rotor, which affects the distribution of the magnetic field inside and outside the machine. Several authors have focused on the exploitation of the axial flux. In fact, if a coil is placed around the machine shaft, it will be the site of an induced electromotive

force. The spectral content of this induced voltage can be used to detect various stator or rotor faults [23].



Figure (I.13): Measurement of axial flux [26].

I.7.1.3. Diagnosis by analysis of induced stator voltages :

J. Milimonfared proposed another technique for detecting rotor faults in induction motors. This technique is based on exploiting the frequency content of the voltage induced by the rotor flux in the stator windings during motor disconnection from the network. The breakage of a bar will directly affect the induced voltage in the stator windings. By using this approach, the effects of non-ideality of the source (imbalances and presence of time harmonics) can be avoided [3]. However, the application of this technique is impossible when it comes to a motor belonging to a production chain.

I.7.1.4. Diagnosis by analysis of electromagnetic torque :

The electromagnetic torque developed in electrical machines comes from the interaction between the stator field and the rotor field. Therefore, any fault, either in the stator or rotor, directly affects the electromagnetic torque. The spectral analysis of this signal provides relevant information about the motor's condition. However, the

need for expensive equipment for acquiring this quantity represents the major disadvantage of this method [5].

I.7.1.5. Diagnosis by analysis of instantaneous power

The use of instantaneous power for fault detection in asynchronous motors has been the subject of numerous studies. It is clear that the level of information carried by the power signal is greater than that provided by the current of a single phase, which represents the advantage of this method compared to others. This method is used for the detection of mechanical faults as well as electrical faults such as short circuits between stator coils. In this regard, (M. Drif et al.) demonstrated the effectiveness of using apparent power for the detection of an eccentricity fault [24].

I.7.1.6. Diagnosis by analysis of stator current :

Among all usable signals, the stator current has proven to be one of the most interesting because it is very easy to access and allows us to detect both electrical and purely mechanical faults. This technique is called "Motor Current Signature Analysis" (MCSA) in the literature. Induction motor faults are reflected in the stator current spectrum by:

The appearance of spectral lines whose frequencies are directly related to the machine rotation frequency, the rotating field frequencies, and the physical parameters of the machine (number of rotor slots and number of pole pairs).

The modification of the amplitude of the spectral lines already present in the current spectrum [3].

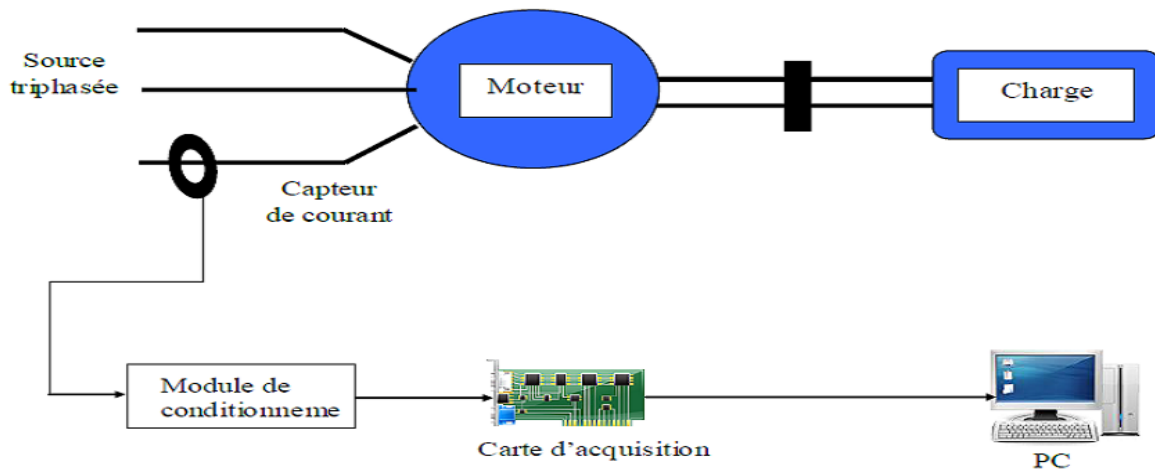


Figure (I.14): Schematic diagram of the principle of the stator current spectrum method [19].

I.7.2. Fault diagnostic methods in MAS

There are numerous and varied diagnostic methods that correspond to the diversity of problems encountered.

I.7.2.1. Diagnostic through chemical analysis

Most engines are air-cooled or, more commonly, cooled using a closed circuit with a water-cooled heat exchanger. The deterioration of electrical insulation in the engine produces carbon monoxide gas, which appears in the cooling air circuit and can be detected using an infrared absorption technique. In some cases, bearing oil is regularly analyzed, and intervention is required if degradation-indicating products are present [25].

I.7.2.2. Diagnostic through temperature analysis

Using infrared devices, hot spots with temperatures that exceed predetermined limits can be detected. To do this, a systematic scan of the entire electrical installation, especially the asynchronous motor, is performed. Since the examined systems are in operation, the elements that make up the electrical installation are under normal load. In fact, they will appear more or less radiant on the infrared image depending on their

role, design, load, and material. The operator distinguishes between normal operating temperatures and anomalies. The anomalies are spatially localized, and adjusting the object's parameters (emissivity, environment, etc.) allows for the direct calculation of the maximum temperature observed and any overheating. In the case where the system is not under normal load, additional calculations can be made to estimate the overheating that would occur under normal operating conditions. Once the overheating is calculated, it can be compared to the degradation kinetics and urgency levels. This determination is crucial because it allows for accurate time localization, which makes managing anomaly treatment easier. A thermal image and a visible light photo can be used to record the fault. Detection would be possible through an analysis of the obtained spectrogram, which would delimit the degraded zones. Excessive friction at the bearings or ball bearings can result in gradual heating that can become significant. Poor contact can generate electrical discharges that indicate a local temperature increase, corrosion, oxidation, a faulty braid, and many other practical examples that can be the subject of thermo graphic inspection [25].

I.7.2.3. Methods based on artificial intelligence

The integration of symbolic and quantitative knowledge, using a neuro-fuzzy system, represents a new research direction in the field of fault detection and localization. Such systems combine the ability of neural networks with the explicit representation of fuzzy logic, which is a significant advantage for solving problems, especially for non-linear systems [25].

I.7.2.4. Diagnostic through parameter identification

Parameter estimation is also well suited to diagnosis. The development of algorithms dedicated to the realistic estimation of physical parameters, taking into account prior knowledge of the machine, has led to a promising advance in induction motor diagnosis through parameter identification. Since this approach is based on identifying the machine's parameters, one of the most important objectives is to develop

mathematically representative models of faulty operation. In a faulty situation, in addition to conventional dynamic behavior, the induction motor exhibits behavior due to faults.

I.8. Conclusion :

In this first chapter, we have presented some reminders on the components of the squirrel-cage induction motor. We have focused on stator windings by detailing frequently encountered faults. Similarly, for the rotor, we have identified the main faults that can occur either during the manufacturing phase or during use.

We will focus this work on the faults of the squirrel-cage induction motor rotor. For this purpose, We will study the harmonics of the stator current to find a specific type of harmonic that can be used as a diagnostic indicator for eccentricity fault. which is the subject of the second chapter of our thesis.

Chapter II

Study of the harmonics of the stator current

II.1. Introduction:

This chapter focuses on the study of harmonics present in the stator current of an induction motor. Harmonics are periodic phenomena that manifest themselves as waves with frequencies that are multiples of the fundamental frequency. In electrical systems, harmonics can cause various problems such as increased losses, reduced efficiency, equipment failures, etc.

The study of harmonics in the stator current of an induction motor is essential to understand the machine's operating characteristics and to detect any potential faults. Spectral analysis techniques, such as Fourier analysis, are used to measure and analyze the waveform of the stator current. By examining the harmonic content of the current, it is possible to identify the specific frequencies and amplitudes of the harmonic components.

Harmonics in the stator current can cause a variety of problems, such as machine overheating, power losses, reduced efficiency, and equipment failures. Therefore, it is important to understand the characteristics of harmonics and their impact on the machine, in order to implement prevention and correction measures.

In this chapter, we will examine the different methods of analyzing harmonics in the stator current, as well as the effects of harmonics on the performance and reliability of the induction motor. We will also study the different diagnostic approaches used to detect machine faults based on the analysis of **TH RSH RBFH EFH** stator current harmonics.

II.2. General theory about the harmonics of the air gap flux:

The air gap flux of a sinusoidally fed induction motor is rich in different harmonics. The analysis shows that these harmonics of air gap flux are due to the interactions of 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 [27].

$$f_{sh1,2}(k) = \left| h \pm \frac{kN_r}{p} (1 - s) \right| \quad k = 1, 2, 3 \dots \quad (\text{II.1})$$

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 also exists a series of harmonics called rotor slot harmonics of order "h" and at frequencies f_{sh} (p, Nr, k).

$$\psi_{sd} = L_{sc} I_{sd} + \sum_{h \in G} \frac{1}{2} \sqrt{\frac{3}{2}} N_r M_{srh} I_{rm} \cos(2\pi f_{sh} t \pm h\varphi_h - \gamma) \quad (\text{II.2})$$

$$\psi_{sq} = L_{sc} I_{sq} + \sum_{h \in G} \frac{1}{2} \sqrt{\frac{3}{2}} N_r M_{srh} I_{rm} \sin(2\pi f_{sh} t \pm h\varphi_h - \gamma) \quad (\text{II.3})$$

I_{rm} : value of the maximum rotor current.

Also note that the derivative of the mathematical expression of the stator direct flux (II.2) with respect to the air-gap length shows that it will be zero except in cases where the air-gap length belongs to the set of values for which the rotor slot harmonics (**RSH**) of order "h" that belong to the set "G" can be detected, as shown in [28]:

$$G = \left\{ \left(h = 1 \cup h = \left(\frac{\lambda N_r}{p} \pm 1 \right)_{\lambda=1,2,3\dots} \right) \cap h = (6v \pm 1)_{v=1,2,3\dots} \right\} \quad (\text{II.4})$$

However, in real-world scenarios, it is very difficult, if not impossible, to find a perfectly balanced power source, a well-centered winding, and an ideally

symmetrical geometry. An 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. Ultimately, this results in harmonics that are not only multiples of 3 but also odd, such as: f_s , $3f_s$, $5f_s$, $9f_s$, etc. We obtain harmonics for both healthy and faulty operation, as shown in [27]:

$$h = (2v \pm 1)_{v=0,1,2,3\dots} \quad (\text{II. 5})$$

In general, we have two sets of harmonics:

1- A series of time harmonics (TH) created by the non-asymmetry of the ($k=0$) fundamental magnetomotive force (f.m.m) with characteristic frequencies [29], [30]:

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

2 - A series of harmonics of rotor slots (**RSH**) with characteristic frequencies [27]:

$$f_{RSH}(h, k, s) = \left| \left(h \pm \frac{kN_r}{p}(1-s) \right) f_s \right| \quad \text{ou} \quad S^\pm = |(hf_s \pm kN_r f_r)| \quad (\text{II. 7})$$

with $h = 1, 3, 5 \dots$

Thus, we can generalize our study, as done previously, to the natural manufacturing imbalance of the rotor, which produces a series of harmonics called "Harmonics of Rotor Bar Fault" (RBFH) that resemble those of theoretical rotor bar breakage.

Moreover, there is also the natural defect of static eccentricity and dynamic eccentricity, which produces mixed eccentricity. This also results in a series of harmonics called "Eccentricity Fault Harmonics" (EFH) [29], [30].

3- A series of harmonics of rotor bar fault (**RBFH**) with characteristic frequencies [30]:

$$f_{RBFH}(h, k, s) = |(h \pm 2ks)f_s| \text{ or } R^\pm = |(h \pm 2ks)f_s| \quad (\text{II. 8})$$

4. A series of mixed eccentricity harmonics called "Eccentricity Fault Harmonics" (EFH) with characteristic frequencies [27]:

$$f_{EFH}(h, k, s) = \left| \left(h \pm \frac{kN_r}{p}(1-s) \right) f_s \right| \text{ or } E^\pm = |(hf_s \pm kf_r)| \quad (\text{II. 9})$$

with $f_r = \frac{kN_r}{p}(1-s)f_s$: is the rotor frequency (see Table IV.1).

II.2.1 Study of the stator current with its harmonics

We will focus our study on phase currents, as the present 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. [29], [31]:

where:

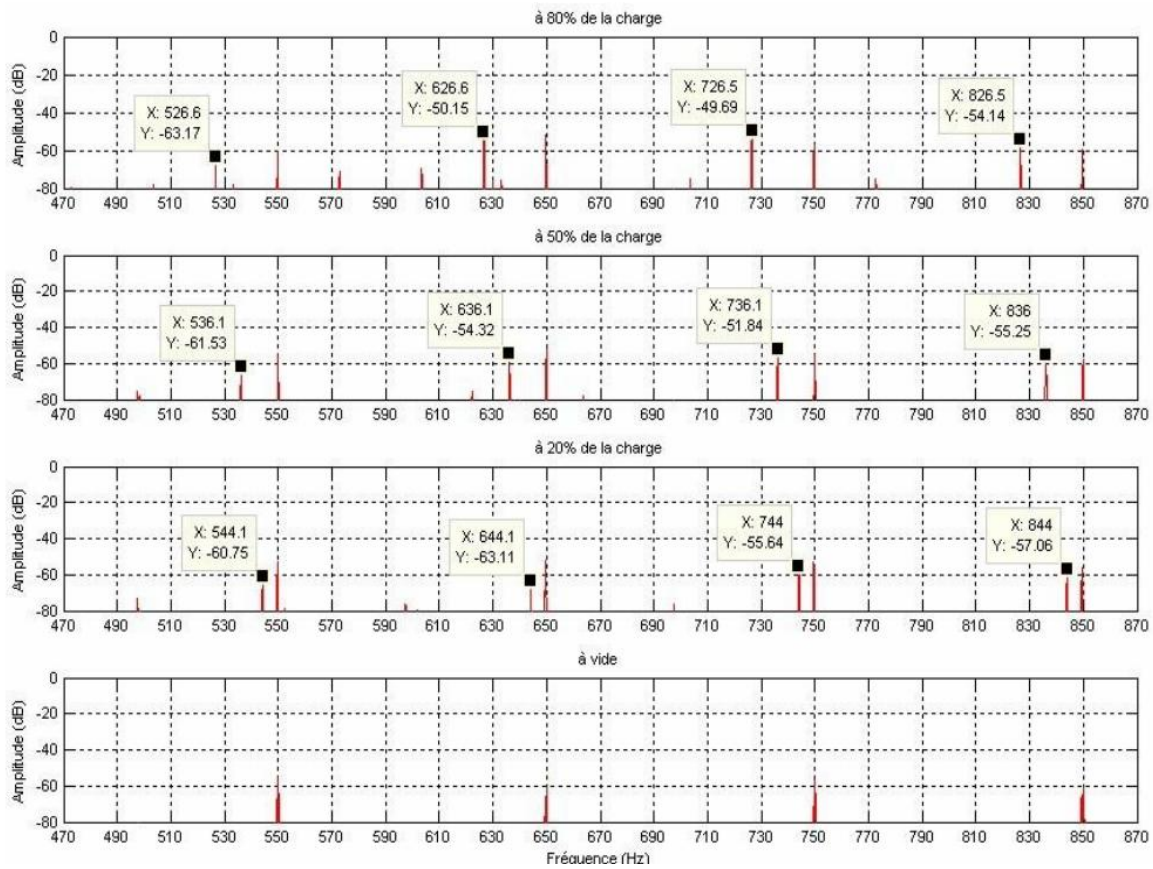
$\hat{I}_{THh}, \hat{I}_{S^\pm k}, \hat{I}_{R^\pm k}, \hat{I}_{E^\pm}$ represents the maximum phase current of the power supply for TH, RSH, RBFH, and EFH harmonics (in amperes) (see Table II.1).

And finally , t temps réel (secondes)

$m = 1,3,5,7,9 \dots$ end $n = 1,2,3,4 \dots$

II.2.2.Spectral analysis of stator current using FFT:

A spectral analysis of the stator current (using Fast Fourier Transform 'FFT') revealed the presence of harmonics that characterize MAS faults.



Fig(II.1) Spectrum of the stator current for different loads [29].

II.3. Fast Fourier Transform

FFT is an efficient method that reduces the number of arithmetic operations required for discrete transformation. Its importance also increases with the evolution of digital signal processing, as well as the possibility of using it for analog signals or more generally for continuous functions in numerous scientific fields. The use of this method is very simple as it does not require the introduction of measuring equipment inside the electrical machine, but rather involves analyzing the stator current of the motor [22] [23] [24].

II.3.1. Applications of FFT on stator currents

To explore the spectral content of stator currents in an asynchronous motor, we will first apply FFT to experimental signals. The results obtained highlight the richness of harmonics in the stator current [30].

Types of harmonics	Their characteristic frequencies.	Their causes.
Time harmonics (TH).	$TH = hfs$	Imposed by the power supply source or winding symmetry.
Harmonics of rotor slots (RSH).	$S \pm = (hfs \pm Nrfr)$	Caused by the structure of the rotor (discrete distribution of rotor bars in the rotor slots).
Harmonics of rotor bar faults (RBFH).	$R \pm = (h \pm 2ks) fs$	Due to the asymmetry of the squirrel-cage rotor.
Harmonics of eccentricity faults (EFH).	$E \pm = (hfs \pm kfr)$	Due to the natural mixed eccentricity of the rotor.

Tab (II.1) Harmonics of stator current.

In Tab. I.1, the spectrum of stator current for operation at 100% of the rated load is shown with the representation of the four families of harmonics (a. TH, b. RSH, c. EFH, and d. RBFH).

❖ **The RSH harmonic:**

For $k=1$ and $v=1$, what is called the RSH harmonic is defined as the principal harmonic of rotor slots.

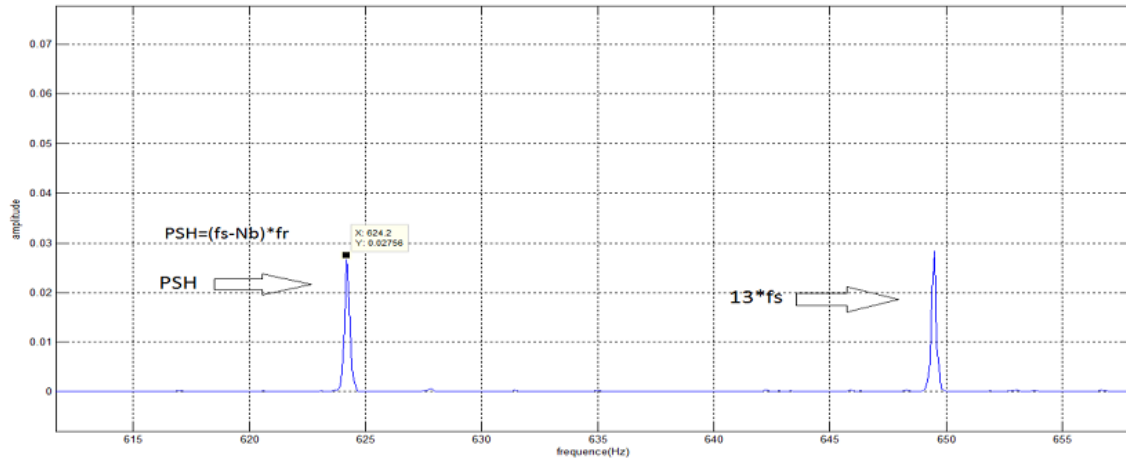


Fig (II. 2) Spectrum of stator current representing the RSH harmonic.

❖ The EFH harmonic:

The rotor eccentricity, also known as airgap eccentricity, airgap non-uniformity, or misalignment, causes this harmonic to appear in case of a fault in the asynchronous motor. [25]

$$EFH = (v.f \pm k.fr)$$

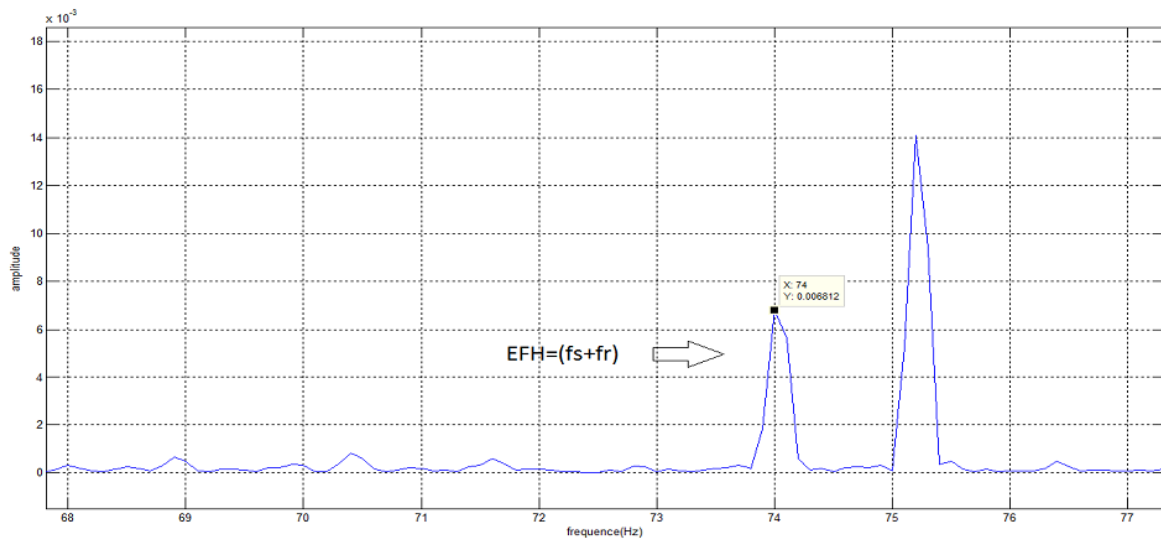


Fig (II.3) Spectrum of stator current representing the EFH harmonic.

❖ RBFH harmonic:

A fault in the rotor creates a kind of asymmetry which, in the case of a supply by a symmetrical three-phase voltage system, results in a rotating magnetic field of inverse frequency $(-gf)$ in the rotor circuit. This generates currents circulating in the stator circuit at a frequency: $f_{\text{RBFH}} = (1-2g)f_s$. This frequency causes modulation of the current, which in turn causes torque oscillations and speed fluctuations. Another component also appears in the spectrum of stator current at a frequency:

$$f_{\text{RBFH}} = (1+2g) f_s.$$

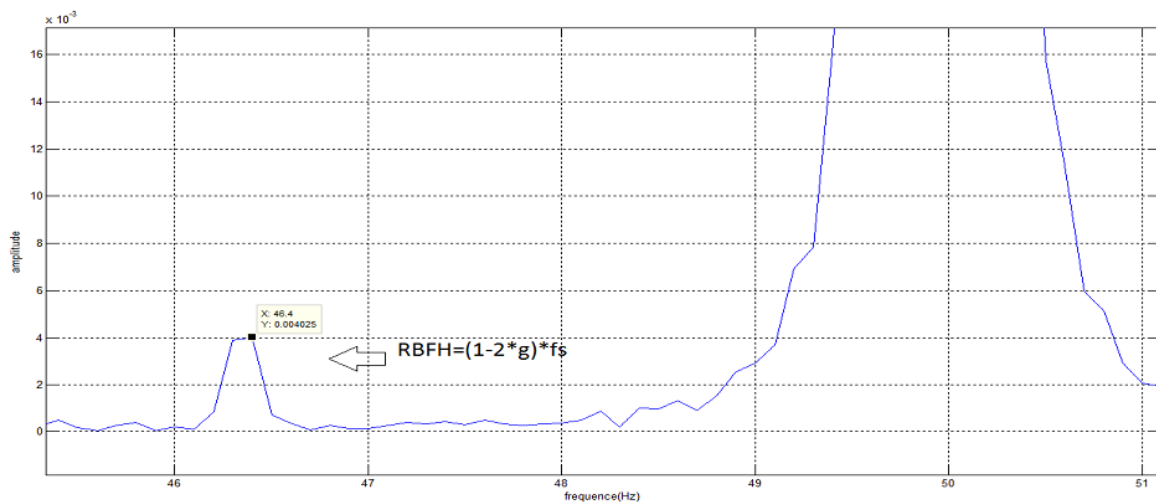


Fig (II. 4) Spectrum of stator current representing the RBFH harmonic.

II.4. Conclusion

Thus, we have come to the end of the introduction to this chapter, which discussed the study of the multiple harmonic frequencies in the stator current TH RSH RBFH EFH of an induction motor. It can be said that the study of multiple harmonic frequencies in the stator current is an important topic in the field of diagnosing faults in electric motors. By understanding the characteristics of multiple harmonic frequencies and their impact on the machine, preventive and corrective measures can be taken to avoid potential problems.

In the next chapter, we will discuss in more detail the methods of analyzing time harmonics in the stator current and their impact on the diagnosis of asynchronous motors to detect eccentricity faults.

Chapter III

Analysis and Discussion of Eccentricity Fault

General conclusion

General conclusion

Based on the results obtained in this work, diagnosing faults in three-phase squirrel-cage induction motors requires the use of advanced and effective techniques. The results gathered through practical experiments on real motors demonstrate that spectral analysis techniques can be effective in detecting different faults in three-phase squirrel-cage induction motors.

However, it should be noted that there is another problem that can affect the performance of these motors, which is rotor deviation from its center. This eccentricity causes distortion in the distribution of the magnetic field in the motor, affecting its performance and increasing the likelihood of faults and malfunctions.

In the first chapter, we provided a review of the components of the squirrel-cage asynchronous machine and highlighted common faults in stator windings. We also identified the main faults that can occur in the rotor during manufacturing or use. Our focus in this work will be on rotor faults of the squirrel-cage asynchronous machine. To achieve this, we will investigate the harmonics of the stator current to identify a specific type of harmonic that can serve as a diagnostic indicator for eccentricity faults. This will be the subject of the second chapter of our thesis.

With this, we conclude the introduction to this chapter, which explored the study of multiple harmonic frequencies in the stator current of an asynchronous machine, including TH, RSH, RBFH, and EFH. The analysis of multiple harmonic frequencies in the stator current is a vital area of research in the field of electric motor fault diagnosis. By comprehending the characteristics of

multiple harmonic frequencies and their impact on the machine, measures can be taken to prevent or address potential problems.

In the upcoming chapter, we will delve deeper into the methods of analyzing time harmonics in the stator current and their significance in diagnosing asynchronous motors for detecting eccentricity faults.

In this chapter, we conducted a thorough analysis to understand and explain all the experimental results. Based on the figures presented, we observed that the average value of the relative amplitude when applying varying loads to the motor showed that the 15th order time harmonic was the most sensitive among the other harmonics.

We can use this TH15 harmonic as a diagnostic indicator for identifying eccentricity faults in induction motors. This can help prevent significant material damage and bodily harm, especially in industries such as chemistry and nuclear power.

Looking ahead, we can incorporate artificial intelligence (AI) for the detection of rotor faults.

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تنازل

نحن الطلبة الآتية أسماءهم في واجهة المذكرة (رقيق إسماعيل . لموشي
زكريا . بن عوالي ايهاب الدين) نتنازل عن ما قمنا به في تجربتنا حول
تشخيص عطل انحراف العضو الدوار للمحرك اللاتزامني والنتائج
المتحصل عليها لصالح الدكتور الفاضل علال عبد الرحيم

وشكرا