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Diagnosis of induction motors by analyzing the harmonics of stator currents (stator fault)

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To all those dear to me, close to my heart.

Who loves me and shares my joy.

TOUFIK

Abstract

Diagnosing stator faults in induction machines plays a crucial role in ensuring the reliable operation of electrical systems. Stator faults lead to reduced motor efficiency, increased energy consumption, and in some cases, complete motor failure. Therefore, the use of spectral analysis and Fast Fourier Transform (FFT) is a fundamental analytical tool in diagnosing these faults. This technique converts signals from the time domain to the frequency domain, enabling the identification of characteristic fault frequencies that indicate specific issues in the stator. This work presents an experimental study of asynchronous machine faults (with and without faults). We proposed a method based on stator current harmonics of induction machines. This technique involves studying the effect of a short circuit on the induction motor, determining the relative sensitivity and the best harmonics for detecting stator faults to be used as indicators for fault diagnosis. This technique is widely applied across various industries to enhance motor reliability, operational efficiency, and maintenance strategies, ensuring continuous and cost-effective motor performance.

Keywords: stator fault, diagnosis, time harmonics, Transform (FFT), induction machines, Fast Fourier, short circuit

Resumé

Le diagnostic des défauts du stator dans les machines à induction joue un rôle crucial dans la garantie du fonctionnement fiable des systèmes électriques. Les défauts du stator entraînent une réduction de l'efficacité du moteur, une augmentation de la consommation d'énergie et, dans certains cas, une défaillance complète du moteur. Par conséquent, l'utilisation de l'analyse spectrale et de la transformation de Fourier rapide (FFT) est un outil analytique fondamental pour diagnostiquer ces défauts. Cette technique convertit les signaux du domaine temporel au domaine fréquentiel, permettant l'identification des fréquences caractéristiques des défauts qui indiquent des problèmes spécifiques dans le stator. Ce travail présente une étude expérimentale des défauts des machines asynchrones (avec et sans défauts). Nous avons proposé une méthode basée sur les harmoniques du courant statorique des machines à induction. Cette technique consiste à étudier l'effet d'un court-circuit sur le moteur à induction, en déterminant la sensibilité relative et les meilleures harmoniques pour détecter les défauts du stator à utiliser comme indicateurs pour le diagnostic des défauts. Cette technique est largement appliquée dans diverses industries pour améliorer la fiabilité des moteurs, l'efficacité opérationnelle et les stratégies de maintenance, assurant des performances continues et rentables des moteurs.

Mots-clés : Défaut du stator, diagnostic, harmoniques temporelles, transformation de Fourier rapide (FFT), machines à induction, Fourier rapide, court-circuit.

ملخص:

يلعب تشخيص أعطال الجزء الثابت في الآلات الحثية دورًا حيويًا في ضمان التشغيل الموثوق للأنظمة الكهربائية. تؤدي أعطال الجزء الثابت إلى تقليل كفاءة المحرك، وزيادة استهلاك الطاقة، وفي بعض الحالات، تؤدي إلى فشل المحرك بالكامل. لذا يعد استخدام التحليل الطيفي وتحويل فورييه السريع (FFT) أداة تحليلية أساسية في تشخيص هذه الأعطال. تقوم هذه التقنية بتحويل الإشارات من المجال الزمني إلى المجال الترددي، مما يمكن من تحديد ترددات الأعطال المميزة التي تشير إلى مشكلات محددة في الجزء الثابت.

يتناول هذا العمل دراسة تجريبية لأعطال الآلات غير المتزامنة (مع وبدون أعطال). وقد اقترحنا طريقة تعتمد على توافقيات تيار الجزء الثابت لآلات الحث. تستند هذه التقنية إلى دراسة تأثير الماس الكهربائي على المحرك الحثي، حيث يتم تحديد الحساسية النسبية وأفضل التوافقيات لاستخدامها كمؤشرات لتشخيص أعطال الجزء الثابت. تُطبق هذه التقنية على نطاق واسع في مختلف الصناعات لتعزيز موثوقية المحركات، وكفاءة التشغيل، واستراتيجيات الصيانة، مما يضمن أداءً مستمرًا وفعالًا من حيث التكلفة للمحركات.

الكلمات مفتاحية : عطل الجزء الثابت، تشخيص، التوافقيات الزمنية، تحويل فورييه السريع(FFT) ، الآلات الحثية، تشخيص، فورييه السريع، ماس كهربائي.

LIST OF SYMBOLS

Ns: number of stator turns per phase
Ωs: synchronous speed
Fs: power supply frequency
: 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.
DC: Bearing diameter
P: Laplace operator
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 Fourier Transform

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General Introduction

General Introduction

Electric motors, particularly induction motors, are critical components in industrial applications due to their robustness, simplicity, and high efficiency. These motors are widely used in various sectors, including manufacturing, transportation, and utilities, owing to their ability to convert electrical energy into mechanical energy with high reliability. However, like all machinery, induction motors are susceptible to faults that can lead to significant operational downtimes and economic losses. Among the various types of faults, stator faults are prevalent and can severely impact motor performance, causing issues such as overheating, reduced efficiency, and eventual motor failure. Therefore, the timely and accurate diagnosis of these faults is crucial to ensure the reliability and efficiency of industrial processes.

One of the most effective techniques for diagnosing stator faults in electric motors is Fast Fourier Transform (FFT). FFT is a mathematical method that transforms time-domain signals into their frequency-domain representations, providing a comprehensive view of the signal's spectral content. This transformation is particularly useful in fault diagnosis because different types of faults often generate characteristic frequency components that can be detected through spectral analysis. For instance, stator faults such as turn-to-turn short circuits and insulation failures produce specific harmonic frequencies that can be identified using FFT. By analyzing these frequency components, it is possible to pinpoint the nature and severity of the faults, facilitating prompt and targeted maintenance actions.

This thesis explores the application of FFT in diagnosing stator faults in induction motors. The primary focus is on identifying specific fault signatures in the frequency spectrum and developing diagnostic algorithms that can reliably detect and classify various stator faults. By leveraging FFT, we aim to enhance the precision and reliability of fault detection, thereby improving maintenance strategies and minimizing unplanned downtimes. The research delves into both the theoretical and practical aspects of FFT application, encompassing signal processing, feature extraction, and algorithm development.

The thesis consists of three chapters. In the first chapter, we present an overview of electrical machines, their types, and the faults they encounter and their causes.

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

The third chapter presents the results of spectral analysis of stator currents and their time harmonics in squirrel-cage asynchronous motors under different operating conditions, with and without faults, and compares them using the Fast Fourier Transform (FFT). In addition to detecting the most sensitive time harmonics

Chapter 01: State of the art on fault diagnosis in the induction machines

I.1 Introduction

Induction motors are generally regarded as one of the most commonly utilized machines in industry and various applications due to several key factors: robustness, simplicity, and reasonable pricing. There are two types of asynchronous motors:

- Single-phase asynchronous motors
- Three-phase asynchronous motors

Three-phase asynchronous motors, in particular, account for over 80% of electric motors used in industrial settings. Their primary function is to convert electrical energy into mechanical energy through electromagnetic phenomena.

This chapter will commence with an introduction to induction machines. Subsequently, we will delve into a range of potential faults affecting them, encompassing fixed part errors, moving part faults, bearing faults, and mechanical faults. Finally, we will explore the prevalent diagnostic methods employed, including monitoring, detection, recognition, and fault localization.

I.2 Induction machines

The induction machine (IM) is highly utilized for powers exceeding a few kilowatts due to its numerous advantages including power density, robustness, ease of implementation, and low cost. The introduction of variable frequency drives in the 1980s greatly facilitated its development by enabling speed control across a wide range. It finds extensive application in various industrial processes such as electric traction, rolling mills, lifting, and pumping, often in conjunction with static converters. Despite its reputation for robustness, the IM, like any electrical machine, is susceptible to electrical or mechanical failures. Consequently, fault diagnosis has become increasingly important in industrial settings over the past two decades due to the significant and costly consequences of faults on industrial processes [1].

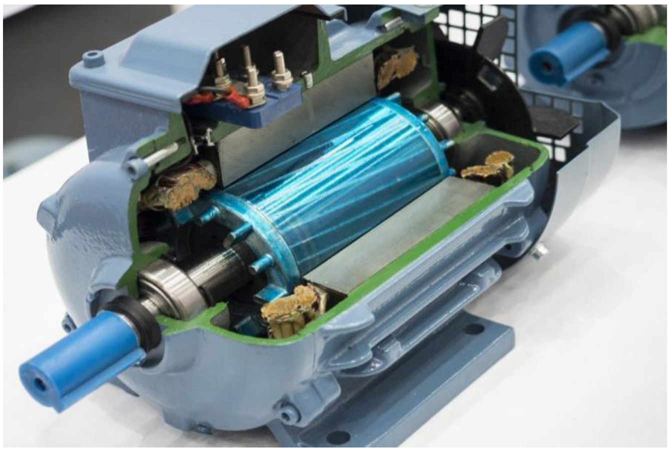


Figure (I.1): Induction machines [2]

I.2.1 Constitution of the induction machines

In this section, we present some of the elements that make up asynchronous machines. This presentation helps us understand how the asynchronous machine is physically constructed.

The three essential parts of a three-phase asynchronous machine are [3] :

The stator: the fixed part of the machine connected to the electrical supply.

The rotor: the rotating part, responsible for turning the mechanical load.

- **The bearings**: mechanical parts that facilitate the rotation of the motor shaft

The components comprising a squirrel-cage induction machine are depicted in Figure I.2

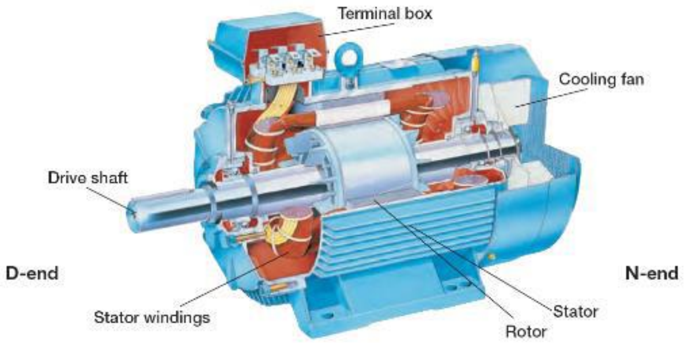


Figure (I.2): Components of a squirrel-cage induction machines [4]

I.2.1.1 The Stator

The stator is the static part of the asynchronous machine and is made of steel sheet to house the windings (coil winding) [5].

This stator winding can be segmented into two components [6]

Slot conductors -

Coil heads -

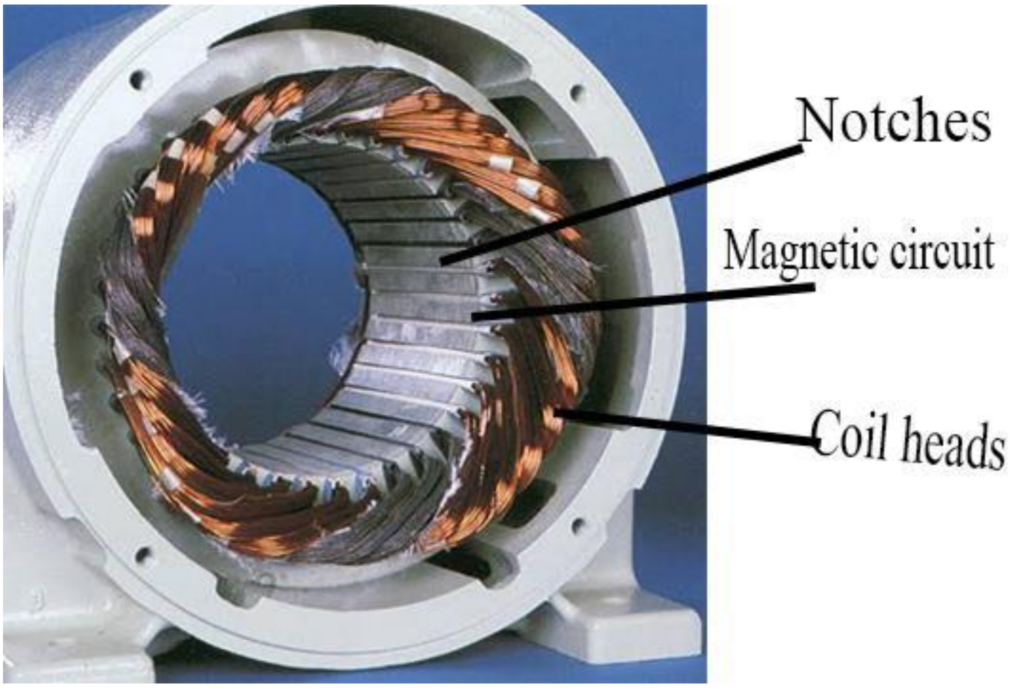


Figure (I.3): Asynchronous Motor Stator [7].

Stator winding is achieved by connecting individual turns in series and parallel. The arrangement of these turns is determined by the desired speed, torque, and supply voltages of the machine.

Insulation is provided by a protective covering, the insulation qualities and heat resistance of which dictate the potential applications of the machine. Additional insulation may be added as necessary. Vibrations and resulting friction accelerate the wear of insulating materials, with heat being the primary factor in their deterioration.

Machines typically incorporate a fan to limit temperature rise, facilitating air passage between the external fins. Dust and moisture accumulation on coil heads weaken electrical insulation.

I.2.1.2 The Squirrel cage rotor

It's the moving part of the motor. Like the magnetic circuit of the stator, it consists of a stack of thin insulated sheets forming a cylinder keyed onto the motor shaft. This element, due to its technology, allows us to distinguish two families of asynchronous motors: those with a "squirrel-cage" rotor, and those with a wound rotor with "slip rings."

In the case of squirrel-cage rotors, the slots can be semi-open or closed. The windings consist of bars short-circuited by an end ring placed at each end of the rotor. The conductors are typically made by casting an aluminum alloy, or by solid copper bars, or occasionally by preformed brass bars pressed into the rotor laminations. There is generally little to no insulation between the rotor bars and the magnetic laminations. Their resistance is sufficiently low so that currents do not flow through the laminations, except when there is a broken bar [8].

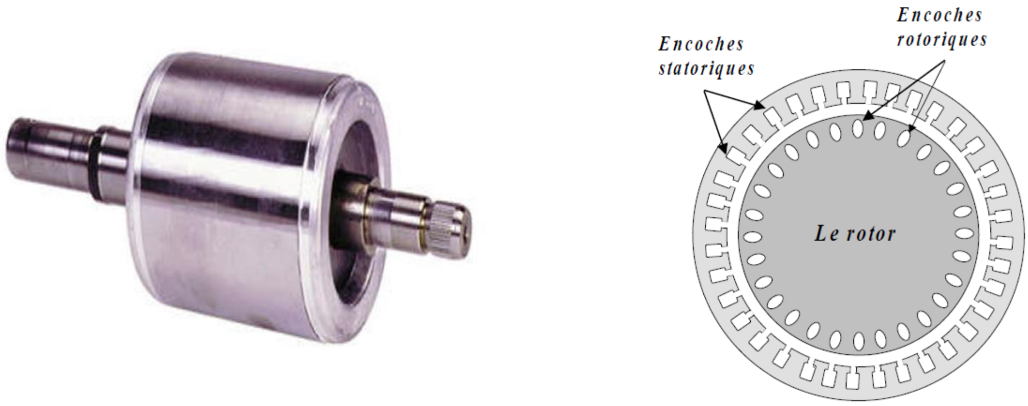


Figure (I.4): Squirrel-cage rotor [8].

I.2.1.3 Mechanical organs

The carcass serves as a casing and provides protection against the external environment. The shaft is a transmission organ. It includes a central part that supports the rotor body and a shaft end to which a half-coupling is attached. It is supported by one or more bearings [9]..

Bearings typically consist of two main components: the flanges and the ball bearings. The flanges are the outer rings of the bearing assembly, providing structural support and alignment for the rotating shaft. They help maintain the position of the bearing within the motor housing and prevent it from shifting during operation [10].

I.2.2. Operating principle of the asynchronous machine

The operating principle of the asynchronous machine is entirely based on the laws of induction. The asynchronous machine is considered as a rotating magnetic field transformer, with the stator comparable to the primary winding and the rotor to the short-circuited secondary winding.

This operation is based on the principle of electromagnetic interaction of the rotating field, created by the three-phase current supplied to the stator winding by the grid, and the currents induced in the rotor winding when its conductors are intersected by the rotating field [11].

In the asynchronous machine, the wave of the rotating field moves in the air gap of the machine with a rotational speed called synchronous speed (Ωs). It is related to the supply frequency (fs) by the following expression [12]:

$$\Omega s = (ws /p) = 60*(fs /p) \qquad (I.1)$$

we have:

fs: frequency of the three-phase voltages of the supply network [Hz].

p: the number of pole pairs.

Certainly! There is always a difference in speed between the stator and the rotor. This difference is known as slip (g), a distinctive characteristic of the asynchronous machine (ASM).

It's defined as the variance in speed between the synchronous speed (Ωs) and the rotor's rotational speed (Ω). The slip (g) can be expressed as [12]:

$$g = (\Omega s - \Omega) / \Omega s \qquad \text{(II.2)}$$

we have:

g: slip.

Ωs: synchronous speed.

Ω: rotor rotation speed.

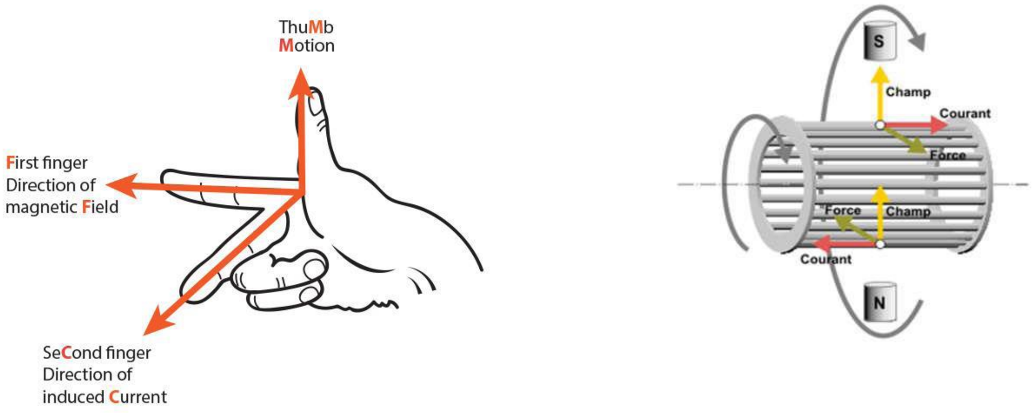


Figure (I.5): Principle of operation of an asynchronous motor [13].

I.3. Presentation of the various malfunctions of the induction machine.

The faults that appear in an asynchronous machine can be divided into two parts: mechanical faults and electrical faults. These faults lead to several problems, where in some cases, they cause the machine to stop unexpectedly, so we must pay special attention to these faults [14].

A statistical study conducted in 1988 by a German industrial systems insurance company on the breakdowns of medium-power asynchronous machines (from 50 kW to 200 kW) yielded the following results (Fig I.6) [9].

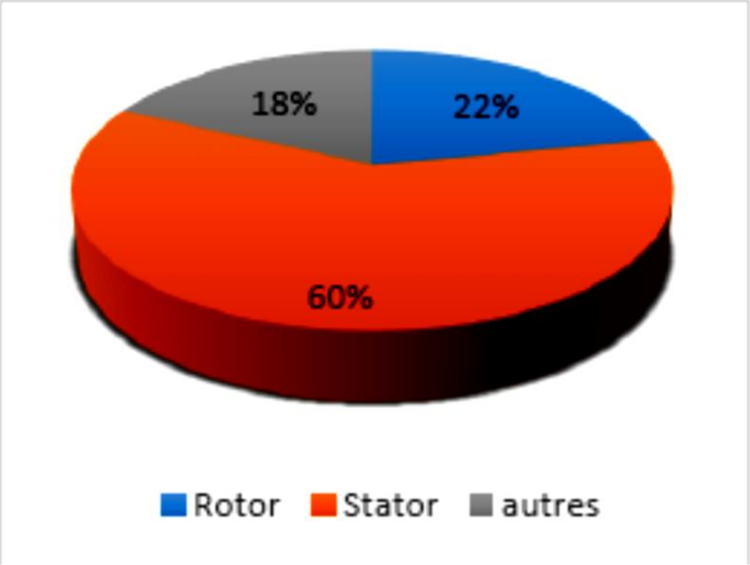


Figure (I.6): Proportion of faults.

I.3.1 Stator faults

Failures in the stator represent approximately 40% to 60% of the faults in asynchronous machines. Since the stator is more subject to electrical stresses than mechanical ones, the main source of faults in an electric motor comes from the windings. Wear effects such as friction or aging of materials have an impact on the integrity of the wires and their insulation. If this insulation is too damaged, these windings can then short-circuit or, when the wire itself is damaged, open circuit. There can be different types of faults with different consequences [1] [15].

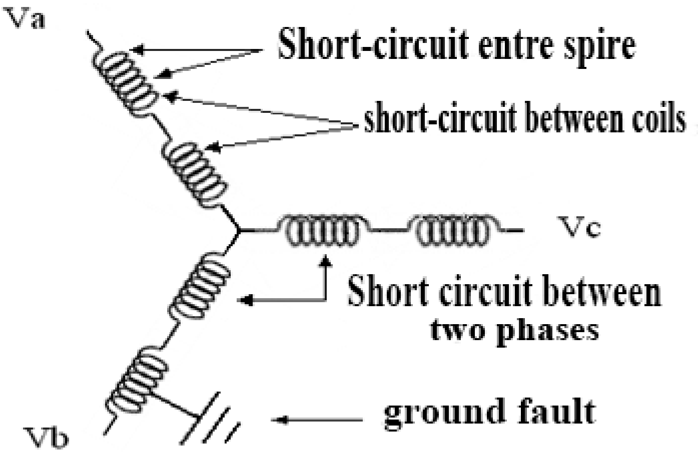


Figure (I.7): The various stator short-circuit faults [15].

I.3.1.1 Short-circuit between stator turns

The short-circuit fault between turns of the same phase is very common in the stator, it can occur either at the coil heads or in the slots, resulting in a decrease in the number of effective turns of the winding. It is mainly due to insulation degradation. However, this fault causes an increase in temperature in the winding and an increase in the intensity of stator currents in the affected phase and a slight variation in amplitude on the other phases, it also modifies the power factor. It amplifies the currents in the rotor circuit. The thermal stress caused by the short-circuit current may lead to the propagation of the fault to other turns [16] [17].

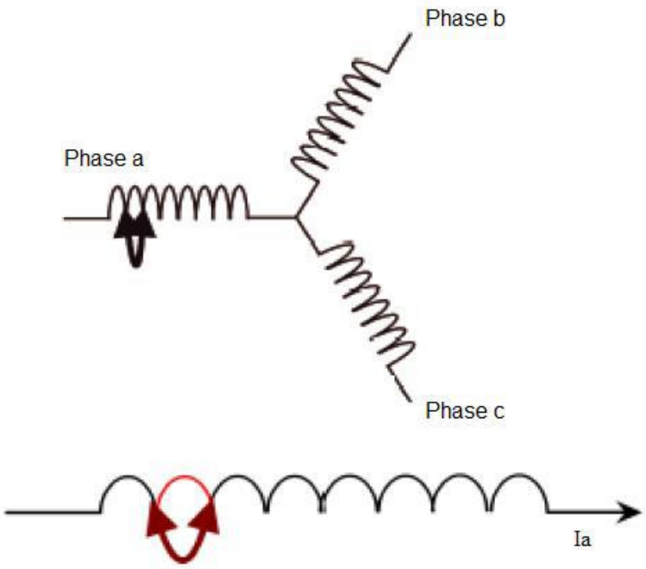


Figure (I.8): Stator turn short-circuit [16].

I.3.1.2 Short-circuit between phases

This fault can occur at any point in the winding, but the most common ones appear at the coil heads, as it is there that conductors from different phases come into contact. The influence of this type of fault on the operation of the machine depends on the location of the fault (the affected part). If the short-circuit is close to the phase supply, it induces very high currents that lead to the melting of the supply conductors, resulting in a sudden stop of the machine. If the short-circuit is close to the neutral between two phases, it causes an imbalance in phase currents with a lower risk of conductor melting. The appearance of this type of fault causes an increase in currents in the bars as well as in the rotor cage rings [1]. This is mentioned in the following Figure 1.11.

Figure (I.9): Short-circuit between phases [1].

I.3.1.3 Insulation faults in a winding

The degradation of insulation in windings can cause short circuits. Indeed, various losses (Joule, iron, mechanical, etc.) lead to an increase in the temperature of the various components of the motor. However, insulation materials have temperature, voltage, and mechanical limits. In this case, a short circuit may occur in the affected winding. The different causes for this type of fault are [18] [19]:

- ✓ Insulation degradation during manufacturing.
- ✓ Winding voltage exceeding the insulation material limit.
- ✓ High current in the winding due to a short circuit, converter fault, or overload
- ✓ Mechanical vibrations.
- ✓ Natural aging of insulation. All insulation materials have a limited lifespan. Even under. normal use, insulation naturally degrades over time.
- ✓ Operation in a severe environment.

I.3.1.4 Defects in magnetic circuit

These flaws frequently lead to an imbalance in the machine's functioning, which, in turn, can worsen the issue through occurrences such as overheating, excessive voltage, notable current surge, and so on.

I.3.1.5 Short circuit in one phase

A short circuit in one phase is one of the most challenging issues to tolerate. In this case, the literature describes the affected phase as lost. On a three-phase machine with a three-arm inverter, this implies the machine's shutdown due to the physical consequences on the motor if the power supply is maintained. The most significant consequence is the occurrence of short-circuit currents. The main issue is the significant heating that can propagate the fault. The magnitude of fault currents depends directly on the number of turns in the short circuit.

I.3.1.6 Open circuit on one phase

An open circuit in one phase has less severe consequences than a short circuit. The opening of one of the phases does not allow fault current to flow and therefore does not pose a heating problem that could deteriorate the rest of the machine. Similarly, an open circuit does not create a resisting torque when a variable field is applied to the coil. The only issue is the loss of one phase and thus the production of torque. In the case of a three-phase motor powered by a three-arm inverter, the only way to ensure minimal operation is to control the remaining two phases, essentially operating like a single-phase machine. The problem then arises from significant torque ripples and the inability to provide service requiring frequent changes in direction of rotation and frequent start/stop phases (passing through zero speed).

I.3.2 Rotor faults

Rotor faults occur at the level of the cage or at the air gap. At the level of the cage, faults consist of broken cage bars or broken short-circuit rings. At the air gap, faults manifest as static, dynamic, or mixed eccentricity [20].

The most recurrent faults, localized at the rotor level, can be defined as follows:

I.3.2.1. Bar breakages

The fracture or breakage of a bar is one of the most common faults in the rotor. It can occur either at its notch or at the end that connects it to the rotor ring. Deterioration of the bars reduces the average value of the electromagnetic torque and increases the amplitude of oscillations, which in turn cause fluctuations in rotational speed, leading to mechanical vibrations and hence abnormal machine operation. The large amplitude of these oscillations accelerates the deterioration of the machine. Thus, the torque decreases significantly with the number of broken bars, inducing a cumulative effect of the failure. The effect of a bar breakage increases rapidly with the number of broken bars[21].

I.3.2.2. Ring breakages

The rupture of a portion of the short-circuit ring in a cage asynchronous machine is a fault that occurs as frequently as bar breakage. These ruptures can be caused by casting bubbles or differential expansions between the bars and the rings. As it is difficult to detect, this fault is generally grouped or even confused with bar breakage in statistical studies. These portions of short-circuit rings carry currents that are higher than those of rotor bars.

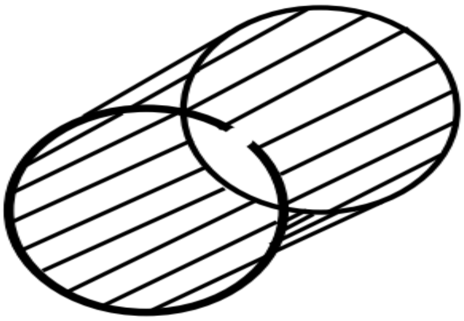


Figure (I.10): Short-circuit ring breakage faults [22].

I.3.3 The mechanical faults

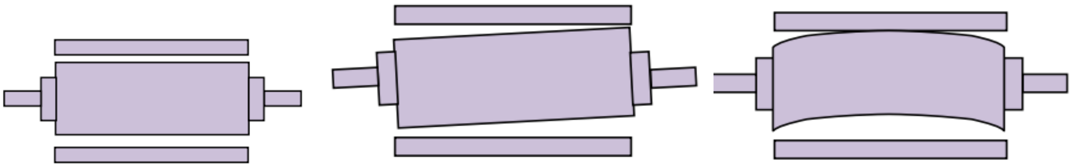
I.3.3.1. Static and dynamic eccentricity

They are mainly due to incorrect positioning of the bearings during assembly, bearing wear, or shaft twisting.

Static eccentricity: the rotor is displaced from the center of the stator bore but still rotates around its axis.

Dynamic eccentricity: the rotor is positioned at the center of the bore but no longer rotates around its axis.

Overall eccentricity combines the two previous cases [23].



a) Static eccentricity b) Dynamic eccentricity c) Mixed eccentricity

Figure (I.11): Representation of static, dynamic, and mixed eccentricity [24].

I.3.3.2. Ball bearings and flanges

This type of defect is most common in high-power machines. It is generally related to bearing wear, specifically degradation of the balls or the raceway.

In the most unfavorable case, the presence of a defective bearing can lead to motor blockage. [9]

Defects created by the flanges of the asynchronous machine are most commonly caused during the manufacturing stage.

Improper positioning of flanges causes misalignment of ball bearings, resulting in eccentricity at the shaft. [2]

I.4 Diagnosis of faults in asynchronous machines

I.4.1 Definition of diagnosis

Diagnosis is the identification of the probable cause of the failure(s) using logical reasoning based on a set of information obtained from an inspection, control, or test.

I.4.2 Diagnostic methods

I.4.2.1 Diagnosis through measurement of axial magnetic leakage flux

In an ideal machine without defects, the stator currents and voltages are balanced, canceling out the axial leakage flux. The presence of any defect causes an electrical and magnetic imbalance at the stator, resulting in the emergence of axial leakage flux with values dependent on the severity of the defect. If a coil is placed around the machine shaft, it will experience an induced electromotive force. The spectral content of the induced voltage in this coil can be utilized to detect various defects [25].

I.4.2.2 Diagnosis through analysis of stator current

Analysis of stator currents in the frequency domain remains the most commonly used method, as the resulting spectrum contains information about the majority of electrical and magnetic faults that may occur within an asynchronous machine. In this frequency analysis, it is preferable to conduct a comprehensive study on the currents because a fault in the rotor is visible in the spectrum of all three line currents [26].

I.4.2.3 Measurement of electromagnetic torque and rotor speed

When a bar breakage occurs, the frequency spectra of rotor speed and electromagnetic torque reveal additional components located at frequencies of 2 times the supply frequency. However, it has been found that the analysis of these components does not provide as much information about the rotor fault as those present in the stator current spectrum (less significant amplitude increases). Furthermore, acquiring these two signals requires equipment that is relatively expensive compared to a simple current sensor, limiting their use for diagnosing faults in asynchronous machines. Some systems reconstruct an image of the electromagnetic torque from the voltages and currents measured on the machine, but this approach remains less effective than the methods previously mentioned [27].

I.4.2.4 Vibration Analysis

Vibration analysis is a prevalent technique employed for identifying mechanical faults in induction machines. The vibrations produced by the machine offer valuable insights into the health of its various components, including bearings, rotor, and stator. By examining the frequency spectrum of the vibration signal, it becomes possible to pinpoint specific fault frequencies associated with particular issues such as bearing defects or rotor imbalance. Vibration analysis encompasses a range of techniques, including frequency analysis, time-domain analysis, and wavelet analysis [28].

I.4.2.5 Methods based on artificial intelligence

Despite the various techniques mentioned earlier, in recent years, the monitoring and detection of faults in electrical machines have moved away from traditional methods towards so-called artificial intelligence techniques. These methods are based on prior knowledge of the system and use a set of rules and facts (data manipulated by the rules) that constitute what is called the knowledge base. Among these methods, we can cite: Fuzzy logic, artificial neural networks (ANN), pattern recognition [29].

I.4.2.6 Model-based diagnostic methods

These diagnostic methods are typically employed based on a physical modeling of the machine. They compare the evolution of the model with that of the physical process and their understanding. According to the understanding of the process, it is possible to define two different formulations of this model-based approach [30]:

Quantitative model-based approach.

Qualitative model-based approach.

I.5 Conclusion

This chapter was dedicated to the structure of the machine and provides a non-exhaustive list of various failures that may occur in the asynchronous machine, along with their causes and consequences. Subsequently, a portion of the various diagnostic techniques for faults in the asynchronous machine was presented.

Chapter 02: Study of the time harmonics of the stator currents

II.1 Introduction

Analysis of time harmonics in stator current is a powerful tool for understanding the electrical state of motors and generators. These periodic fluctuations, which appear at multiples of the fundamental electrical frequency, reveal valuable information through spectrum analysis. Diagnosis of electric motors is mainly based on spectrum analysis of several signals, such as stator currents, torque, vibrations, leakage fluxes, speed and power. These signals are one of the most common ways to detect mechanical or electrical faults in motors. Therefore, by detecting and analyzing these harmonics, engineers are able to diagnose various problems, such as load unbalances, coil faults, core saturation, and power problems. Simulations do not provide real and accurate answers, therefore we need to conduct comparative studies between different diagnostic methods to determine which methods are most sensitive to the defects we encounter. Thanks to this study and analysis, we are able to have a deeper understanding of the electrical behavior of the machine, which enables informed decisions and effective solutions to be made.

II.2. The definition of harmonic

An harmonic is defined as a sinusoidal component of a periodic signal, having a frequency multiple of the fundamental wave. The frequency domain corresponding to the study of harmonics is generally between 100 Hz and 2000 Hz (between the harmonic ranks h=2 and h=40). However, sub-harmonics or inter-harmonics can be observed at frequencies that are not integer multiples of the fundamental frequency [31].

Any periodic function can be represented by a Fourier series in the form:

$$y(t) = Y_0 + \sum_{h=1}^{\infty} Y_h \cdot \sqrt{2} \cdot \sin(\mathrm{h}\omega\mathrm{t} - \varphi_h)$$

Y_h: Effective value of the harmonic component of rank h.
φ_h: Phase of the h component when $\mathrm{t} = 0$.
Y_0: Mean value or DC component of the signal y(t).
ω: Fundamental angular frequency ($2\pi.\mathrm{f} = 2\pi/\mathrm{T}$).
h: Harmonic rank.

II.3 Current and voltage harmonic

The harmonics present on electrical networks originate from the use of non-linear loads. When they are connected to the network at a certain frequency, they absorb a non-sinusoidal current but of the same frequency [32].

These loads behave like harmonic current sources, meaning that the current is determined by the load and not by the network voltage. These currents cause harmonic voltage drops in the network according to Ohm's law:

$$V_h = Z_h I_h$$

Vh: Harmonic voltage of rank h;

Zh: Harmonic impedances of rank h;

Ih: Harmonic current of rank h.

II.4 Origins and sources of harmonics

II.4.1 Static converters

Static converters utilizing electronic components such as diodes and transistors generate harmonic currents [33], thereby affecting the power factor. However, it's important to note that symmetric loads do not produce even-order harmonics. Furthermore, the harmonic spectrum is decreasing, with the third harmonic being predominant. For single-phase loads, it can reach up to 80% of the fundamental [34].

Static converters are the most troublesome sources of harmonics due to the number and power of the installed devices. Non-exhaustively, these include:

Single-phase and three-phase rectifiers-

Dimmers used in drives-

-Lighting and heating systems and network control systems

-Electronic variable speed drives consisting mainly of a static converter and an electronic part, intended to control the speed of an electric motor.

II.4.2 saturated inductors

The impedance of such inductors is proportional to the amplitude of the current flowing through them, and they indeed induce significant current distortions. To some extent, this holds true for transformers operating under no-load conditions, which are subject to persistent overvoltage.

II.4.3 Lighting

Harmonic currents are generated by discharge lamps and fluorescent tubes. For certain modern compact fluorescent lamps, the individual harmonic rate 3 can even exceed 100%, requiring special attention to determining the cross-section and protection of the neutral conductor. Carrying the sum of the third harmonic currents from the three phases, it risks significant heating.

II.4.4 Rotating machines

Rotating machines produce high-order tooth harmonics with amplitudes that are often negligible[33].

II.4.5 Arc furnaces

The arc in an AC arc furnace is nonlinear, asymmetric, and unstable. It generates spectra with odd, even, and continuous lines (background noise at all frequencies). The spectrum level is determined by the type of furnace, its power, and the operating period (melting, refining, etc.). Furthermore, only measurements allow for precise estimation of the spectrum.

In the case of a DC arc furnace, the arc is supplied by a rectifier. Unlike alternating current, the arc is more stable. The current absorbed has a spectrum similar to that of a rectifier and a continuous spectrum with a lower level than that of an AC furnace.

II.5 Effects of harmonic disturbances

The harmonic voltages and currents, which superimpose on the fundamental wave, exert a combined influence on the devices and equipment connected to the electrical network. These harmonic components, whose frequencies are integer multiples of the fundamental frequency (50 Hz for European networks), generate distinct effects depending on the nature of the receivers to which they are subjected [32].

II.5.1 Instant effects

The instantaneous effects are the immediate effects on the operation of a device such as the noise that can appear in a telephone device.

The instantaneous effects concern devices producing an electronic image (computer screen, television), devices producing sound supposed to be of good quality (HI-FI system, telephone), or the precision of measuring devices. Harmonics can lead to malfunctioning of electronic systems using voltage as a reference. Energy meters exhibit additional errors in the presence of harmonics. Harmonic currents generate vibrations and acoustic noises in electromagnetic devices such as transformers, inductors, and rotating machines [31].

Disturbances occur when a low-current line runs along an electrical distribution pipeline with distorted currents and voltages.

II.5.2 Delayed effects

Delayed effects are those that manifest after a more or less prolonged exposure to a phenomenon. They result in a partial loss of functionality, unavailability, or even complete destruction of the device. Delayed effects can be classified according to the time before deterioration. A distinction is made between short-term effects (up to a few seconds), medium-term effects (from a few seconds to a few hours), and long-term effects (from a few hours to a few years).

The delayed effects are often related to more or less significant overheating. These effects are essentially due to two phenomena:

- Heating of the conductors or components traversed by harmonic currents;
- Aging of the insulators, which can be due either to a tension stress resulting from the presence of harmonic voltages, and thus to a local increase in leakage currents, or to excessive heating of the conductors. The impact of a harmonic disturbance on a given device depends on the time constants and heating involved and the level of disturbance.

II.5.3 Short-term effects

They essentially concern two types of equipment:

- Components with low thermal time constants such as the power stages of electronic devices.
- Elements likely to resonate or located on the path of a current amplified by resonance, such as capacitors, circuit breakers, or small transformers.

II.5.4 Medium and long term effects

For medium and long-term effects, cables can experience overheating of the neutral conductor, as well as switching devices and wound equipment such as transformers or motors. For medium-term effects, there are generally significant levels of harmonic voltage on the network, which allows for relatively easy diagnosis.

Long-term effects concern all types of equipment and are related to the presence of lower levels of harmonics. They result in premature aging of motors, transformers, cables, and surge protectors. Long-term effects are not easy to conclusively link to the presence of harmonics.

II.6 Characteristics of harmonic pollution

In industry, the distortion of voltage or current is described by three indices: the crest factor (Fc), the distortion factor (Fdis), and the total harmonic distortion (THD) rate [35].

- ✓ **Peak factor**

By definition, the peak factor of a voltage is equal to the peak value divided by the effective value. For a sinusoidal voltage (which obviously has no distortion), the peak factor has a value of $\sqrt{2}$.

- ✓ **Harmonic distortion rate**

The THD of a current or voltage is equal to the root mean square (RMS) value of all harmonics divided by the RMS value of the total current. It is often used to quantify the distortion of voltage and/or current waves.

In the case of a current laden with harmonics, the THD is given by the expression:

$$\mathrm{THD}(\%) = \frac{\mathrm{I_h}}{\mathrm{I}}$$

With:

$$I = \sqrt{I_1^2 + \cdots + I_h^2}$$

I: effective value of current

$$\mathrm{I_h} = \sqrt{\mathrm{I_2^2} + \mathrm{I_3^2} \ldots + \mathrm{I_n^2}}$$

With: Ih: the effective value of all the harmonics of the current

For a voltage, the THD is given by the analogous formula:

$$\mathrm{THD} = \frac{\mathrm{E_h}}{\mathrm{E}}$$

with: $\mathrm{E} = \sqrt{\mathrm{E_1^2} + \mathrm{E_2^2} \ldots + \mathrm{E_n^2}}$

E: effective value of the voltage.

$$\mathrm{E_h} = \sqrt{\mathrm{E_2^2} + \mathrm{E_3^2} \ldots + \mathrm{E_n^2}}$$

Eh: Effective value of the entire voltage harmonics.

- ✓ **The distortion factor Fdis.**

The distortion factor, denoted as Fdis and given by equation (I-7), informs us about the distorting power generated by the harmonics, as seen in equation (I-8).

$$\mathrm{Fdis}\ = \frac{I_1}{I}$$

$$\mathrm{D} = \mathrm{S}\sqrt{1-(\mathrm{F_{dis}})^2}$$

Where S represents the apparent power $S = \sqrt{P^2 + Q^2}$

P and Q being the active and reactive powers respectively.

II.7 General theory of Asynchronous machine harmonics

In the context of an induction motor powered by a sinusoidal current, the air gap field exhibits a variety of harmonics. Analysis reveals that these harmonics of the air gap flux arise from interactions between the air gap permeance and harmonics of the magnetomotive force (f.m.m.). Research has confirmed that harmonics of rotor slots, termed "Rotor Slots Harmonics" (**RSH**), are generated in the stator current line for a healthy machine at specific frequencies determined by [36] :

$$f_{sh1,2}(k) = \left|\left(h \pm \frac{kN_r}{p}(1-s)\right)f_s\right|_{k=1.23\ldots} \quad (\mathrm{II.1})$$

As evident from the mathematical expressions (IV.2) for direct flux and (IV.3) for indirect flux, in addition to the fundamental component, there exists a series of harmonics known as rotor slot harmonics of order "h" and with frequencies fsh (p, Nr, k). given by:

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

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

: *maximum rotor current value.*

It is noteworthy that the derivative of the mathematical expression for the stator direct flux (II.2) indicates that it will be zero except when "h" belongs to the set "G". Consequently, only the **RSH** of order "h" that belong to the set "G" can be detected, as shown in [37]:

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

However, in real-world scenarios, it is very difficult to find a perfectly balanced power source, and in some cases, it may even be impossible to achieve. Additionally, achieving a well-centered winding and ideally symmetric geometry is challenging. Any imbalance in voltages will lead to the creation of negative sequence currents (reverse field) in the stator windings, giving rise to other harmonic frequencies in the stator windings. Ultimately, this results in harmonics that are not only multiples of 3 but also odd multiples such as: fs, 3fs, 5fs, 9fs, and so forth. We obtain harmonics whether the operation is healthy or faulty, as stated in [36].

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

In general, we have two sets of harmonics:

1- A set of time harmonics (**TH**) created by the non-asymmetry of the f.m.m with (k = 0) of characteristic frequencies [38], [39].

fTH (h) = hfsou TH =hfs (II.6)

2- A series of harmonics of rotor slots (**RSH**) with characteristic frequencies [36] :

$fRSH\ (h, k, s) = |(h \pm \frac{\mathrm{kNr}}{\mathrm{p}}\ (1 - s))\ fS\ |\ or\ S\pm = (hfS \pm kNrfr\ )$ (II.7)

With h=1,3,5 …

Following the same approach as previously, we can extend our analysis to the inherent manufacturing imbalances in the rotor, which give rise to a series of harmonics known as "Harmonics of Rotor Bar Fault" (RBFH) that resemble those of theoretical rotor bar breakage.

Additionally, there are two types of natural eccentricity faults: static eccentricity and dynamic eccentricity, which combine to produce mixed eccentricity. This mixed eccentricity fault also generates a series of harmonics known as "Eccentricity Fault Harmonics" (EFH) [38], [39].

3- A series of harmonics of rotor bar faults (RBFH) with characteristic frequencies [39]:

$fRBFH\ (h, k, s) = (\ h \pm 2ks\ )fs\ or\ R\pm = (\ h \pm 2ks\ )fs$ (II.8)

4- A series of eccentricity fault harmonics (EFH) with characteristic frequencies [36]:

$(\mathbf{h},\mathbf{k},\mathbf{s}) = |(\mathrm{h} \pm \mathbf{fEFH}(\mathbf{h},\mathbf{k},\mathbf{s})\ \frac{\mathrm{kNr}}{\mathrm{p}}\ (1 - \mathrm{s})\ \mathrm{fs}|$ or $\boldsymbol{E}\pm = |(\ \mathbf{h}\boldsymbol{fs} \pm \mathbf{kf}\boldsymbol{r})\ |$ (II.9)

With $f_r == (\frac{\mathrm{Nr}}{\mathrm{p}}\ (1 - s))\ fS$

II.8 Investigation of stator current and its harmonics

Our study will center on phase currents, as this work primarily revolves around analyzing the existing harmonic spectrum. Consequently, we'll substitute the aforementioned harmonics (II.6) - (II.9) in the expressions provided by the instantaneous currents flowing through the three phases "a", "b", and "c" of our asynchronous motor. These equations are presented in (II.10) [38], [40].

With:

IˆTHh , Iˆs± k ,IˆR k , IˆE±k are, respectively, the maximum supply phase current

for TH , RSH, RBFH and EFH (amperes)(see Tab.II.1), and finally , t : is the real time (seconds). with m =1,3,5,7,9,... and n =1,2,3,4…

$$\begin{cases} i_{sa}(t)_{sain} = \sum_{h=1}^{m}\left[\hat{I}_{THh}\cos(2\pi THt) + \sum_{k=1}^{n}\left[\hat{I}_{S^{\pm}h}\cos(2\pi S^{\pm}t) + \hat{I}_{R^{\pm}k}\cos(2\pi R^{\pm}t)\right.\right. \\ \qquad \left.\left. + \hat{I}_{E^{\pm}k}\cos(2\pi E^{\pm}t)\right]\right] \\ i_{sb}(t)_{ssai} = \sum_{h=1}^{m}\left[\hat{I}_{THh}\cos\left(2\pi THt - \frac{2\pi}{3}\right) + \sum_{k=1}^{n}\left[\hat{I}_{S^{\pm}h}\cos\left(2\pi S^{\pm}t - \frac{2\pi}{3}\right)\right.\right. \\ \qquad \left.\left. + \hat{I}_{R^{\pm}k}\cos\left(2\pi R^{\pm}t - \frac{2\pi}{3}\right) + \hat{I}_{E^{\pm}k}\cos\left(2\pi E^{\pm}t - \frac{2\pi}{3}\right)\right]\right] \\ i_{sc}(t)_{sain} = \sum_{h=1}^{m}\left[\hat{I}_{THh}\cos\left(2\pi THt - \frac{4\pi}{3}\right) + \sum_{k=1}^{n}\left[\hat{I}_{S^{\pm}h}\cos\left(2\pi S^{\pm}t - \frac{4\pi}{3}\right)\right.\right. \\ \qquad \left.\left. + \hat{I}_{R^{\pm}k}\cos\left(2\pi R^{\pm}t - \frac{4\pi}{3}\right) + \hat{I}_{E^{\pm}k}\cos\left(2\pi E^{\pm}t - \frac{4\pi}{3}\right)\right]\right] \end{cases}$$

(II.10)

Table.II.1 General expression of the different harmonics of the stator current [36]

Types of harmonics	**Their frequencies features**	**Their causes**
Time harmonics **(TH):**	$TH = hfs$	Caused by the power source or winding asymmetry
Rotor Slot Harmonics **(RSH)**	$S\pm = \lvert(hfs \pm Nr\ fr\ )\rvert$	Caused by the rotor structure (discrete distribution of rotor bars in the rotor slots)
Rotor Bar Fault Harmonics **(RBFH)**	$R\pm = \lvert(h \pm 2ks)fs\ \rvert$	Due to the asymmetry of the squirrel-cage rotor
Fault harmonics of eccentricity (EFH)	$E\pm = \lvert(hfs \pm kfr)\rvert$	Due to the natural mixed eccentricity of the rotor

In the analysis of electric motors, the Park transformation is a mathematical tool used to convert a three-phase system (represented by phases a, b, and c) into a two-phase system (represented by d and q components). The transformation expression is presented by [36]:

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

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

In the ideal case, where there is only the fundamental harmonic, the Park vector currents isq(t)et isd(t) and in Eqs (II.11) and (II.12) can be simplified as follows [41]:

$$i_{sd}(t)_{\text{sain}} = \frac{\sqrt{6}}{2}\hat{I}_{TH1}\sin(2\pi f_s t) \qquad \text{(II. 13)}$$

$$i_{sq}(t)_{\text{sain}} = \frac{\sqrt{6}}{2}\hat{I}_{TH1}\cos(2\pi f_s t) \qquad \text{(II. 14)}$$

In the real operating scenario, where there naturally exists a voltage source imbalance or winding asymmetry, asymmetry of the rotor of the squirrel-cage, and natural mixed eccentricity of the rotor, after substitution into Eq (II.13) and (II.13), we find the following expressions [36], [40]:

$$i_{sd}(t)_{s\text{sin}} = \frac{\sqrt{6}}{2}\left[\sum_{h=1}^{m}\left[\hat{I}_{THh}\sin(2\pi THt) + \sum_{k=1}^{n}\left[\hat{I}_{S^{\pm}h}\sin(2\pi S^{\pm}t) + \hat{I}_{R^{\pm}k}\sin(2\pi R^{\pm}t) + \hat{I}_{E^{\pm}k}\sin(2\pi E^{\pm}t)\right]\right]\right] \qquad \text{(II. 15)}$$

$$i_{sq}(t)_{\text{sain}} = \frac{\sqrt{6}}{2}\left[\sum_{h=1}^{m}\left[\hat{I}_{THh}\cos(2\pi THt) + \sum_{k=1}^{n}\left[\hat{I}_{S^{\pm}h}\cos(2\pi S^{\pm}t) + \hat{I}_{R^{\pm}k}\cos(2\pi R^{\pm}t) + \hat{I}_{E^{\pm}k}\cos(2\pi E^{\pm}t)\right]\right]\right] \qquad \text{(II. 16)}$$

II.9 Description of The experiment and the equipment utilized

In the laboratory of the Faculty of Technology at the University of El Oued, we, as students, conducted an experiment under the guidance of our supervising professor. The experiment focused on analyzing electrical motors using various equipment and tools. Various tools and techniques will be used to analyze defects, such as electrical current tests. The results obtained will be compared with approved standards for the performance of sound electric motors to determine the extent to which defects affect performance.

II.9.1 Test bench

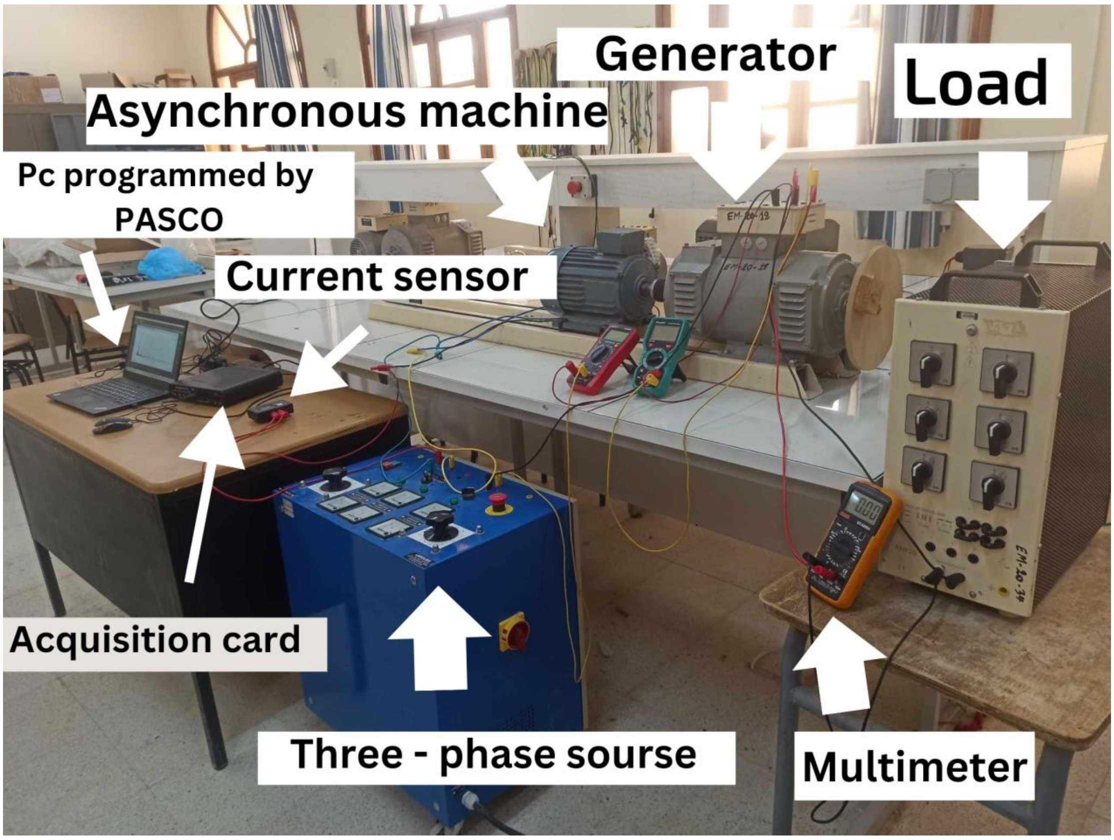


Fig.III.1 Experimental test bench

II.9.2 Materials used

The experiment explores how an asynchronous machine performs under different load levels. By measuring factors such as the stator current, at each stage we changed the applied load. The investigation included two phases: a healthy engine test and a faulty engine test. We also took several results at each stage to ensure the reliability of the data by reducing errors during data collection.

Below we mention the equipment we used in our experiment:

- ✓ **Three-phase source:** This supplies the electrical power for the experiment.
- ✓ **Asynchronous machine:** This is the device under test in the experiment. An asynchronous machine, also known as an induction motor, is a type of electric motor that converts AC electrical energy into mechanical energy.
- ✓ **Generator:** This converts mechanical energy into electrical energy.
- ✓ **Load:** This is a device that absorbs energy from the asynchronous device. The values that the load takes are variable according to experience.
- ✓ **Current sensor:** This device measures the electric current flowing in a circuit. The current sensor in the image is connected to the asynchronous machine.

- ✓ **Acquisition card:** This device captures and converts analog signals from the current sensor into digital signals that a computer can understand.
- ✓ **Multimeter:** This is a versatile instrument that can measure voltage, current, and resistance.
- ✓ **PC programmed by PASCO:** PASCO is a provider of science laboratory equipment and software. The computer in the experiment runs the PASCO software, which controls the experiment and collects data from the acquisition card.

II.10 Conclusion

In conclusion, this chapter discusses the concept of harmonic time, its applications, sources, and effects. Whereas, time harmonics are one of the most popular modern methods for diagnosing electrical machines. As the most efficient and easiest to use in diagnosis. In the next chapter, we will rely on time harmonics to obtain experimental results.

.

Chapter 03 : Experimental result

III.1 Introduction

In this chapter, we will examine and analyze the results obtained to determine the impact of stator coil malfunctions on the performance of electric motors. We will test and monitor an electric motor with intentionally manufactured defects in the stator windings. The resulting data will be analyzed to identify these defects and assess their impact. Various diagnostic tools, such as electrical current tests, will be employed to analyze the faults. The obtained results will be compared to the approved performance standards of intact motors to gauge the extent of performance degradation caused by the faults. Special attention will be given to the analysis of harmonic distortion current in the stator, comparing data collected from both healthy and defective motors under various operating conditions.

III.2 Results of the Stator Current Experiments:

III.2.1. Case of a healthy machine:

We conducted three experiments with variable loads to confirm and compare the results throughout the testing. The results for a healthy machine are as follows:

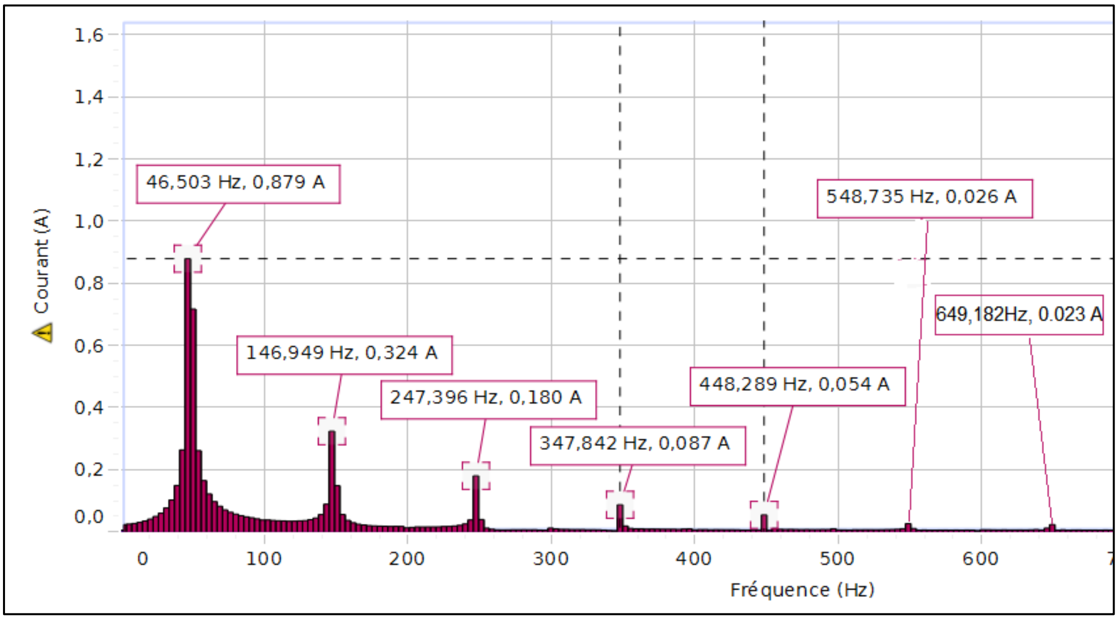


Figure (III.1): Stator current spectrum of a healthy motor at 0% load (Test 1)

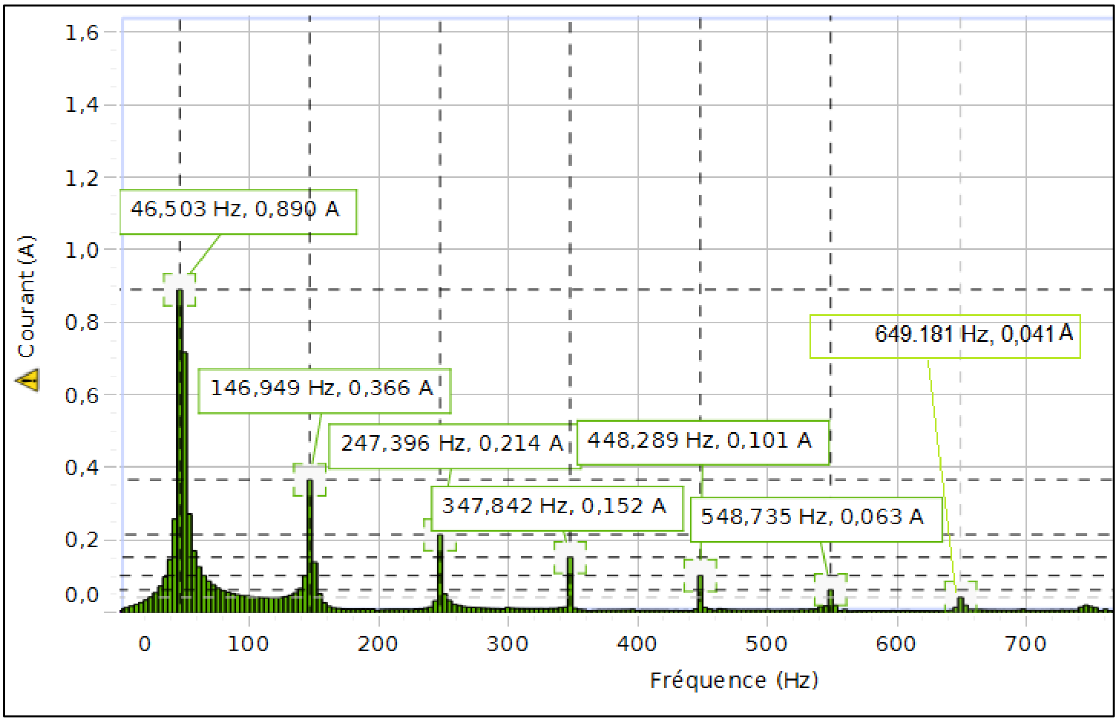


Figure (III.2): Stator current spectrum of a healthy motor at 15 % load (Test 2)

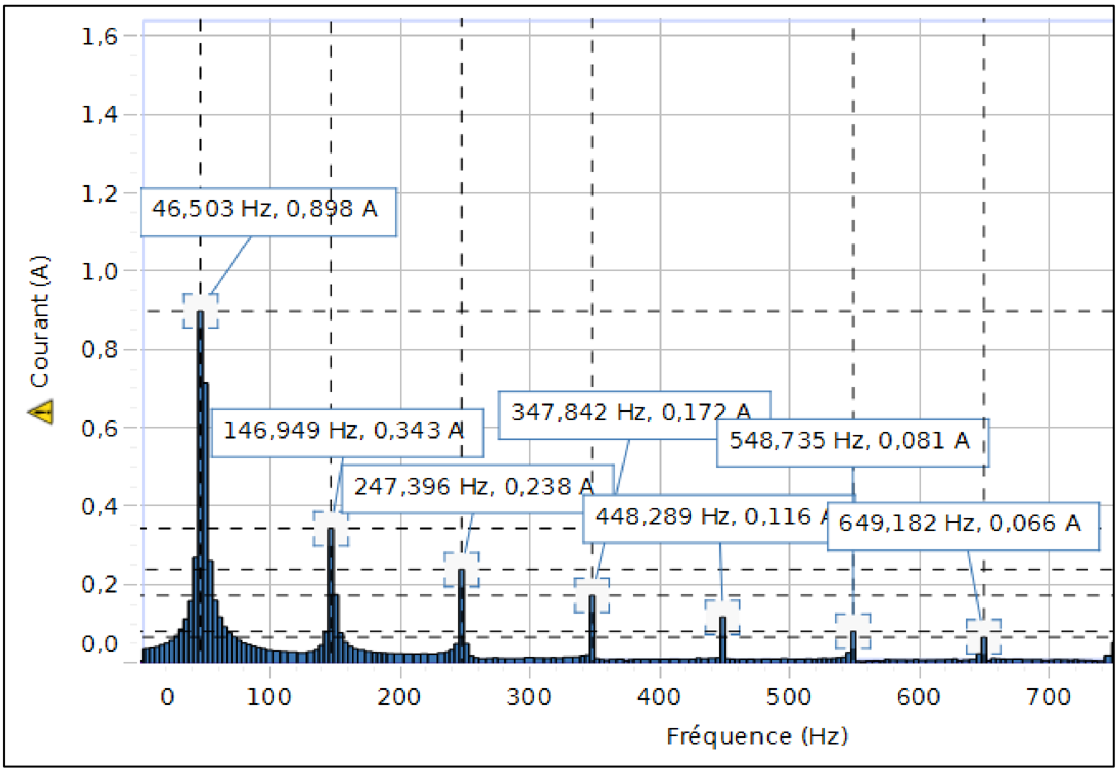


Figure (III.3): Stator current spectrum of a healthy motor at 45 % load (Test 3)

The results of the amplitudes of the different harmonics of the stator current for a healthy motor are recorded in the following table :

Table III.1: Amplitudes of the different harmonics in the stator current of a healthy motor

Harmonic time range	TH1	TH3	TH5	TH7	TH9	TH11	TH13
Frequencies $TH_h = f_s$ (Hz)	50	150	250	350	450	550	650
Amplitudes	ATs-1	ATs-3	ATs-5	ATs-7	ATs-9	ATs-11	ATs-13
ATs1 (A) Test 1, At 0% load	0.879	0.324	0.180	0.087	0.054	0.026	0.023
ATs2 (A) Test 2, At 15% load	0.890	0.366	0.214	0.152	0.101	0.063	0.041
ATs3 (A) Test 3 , At 45% load	0.898	0.343	0.238	0.172	0.116	0.081	0.066

III.2.2. Case of a machine with stator faults:

- **For a short circuit**

We have three experiments with a faulty motor and at different loads to confirm and compare the results. The consequences in case of a faulty motor are the following**:**

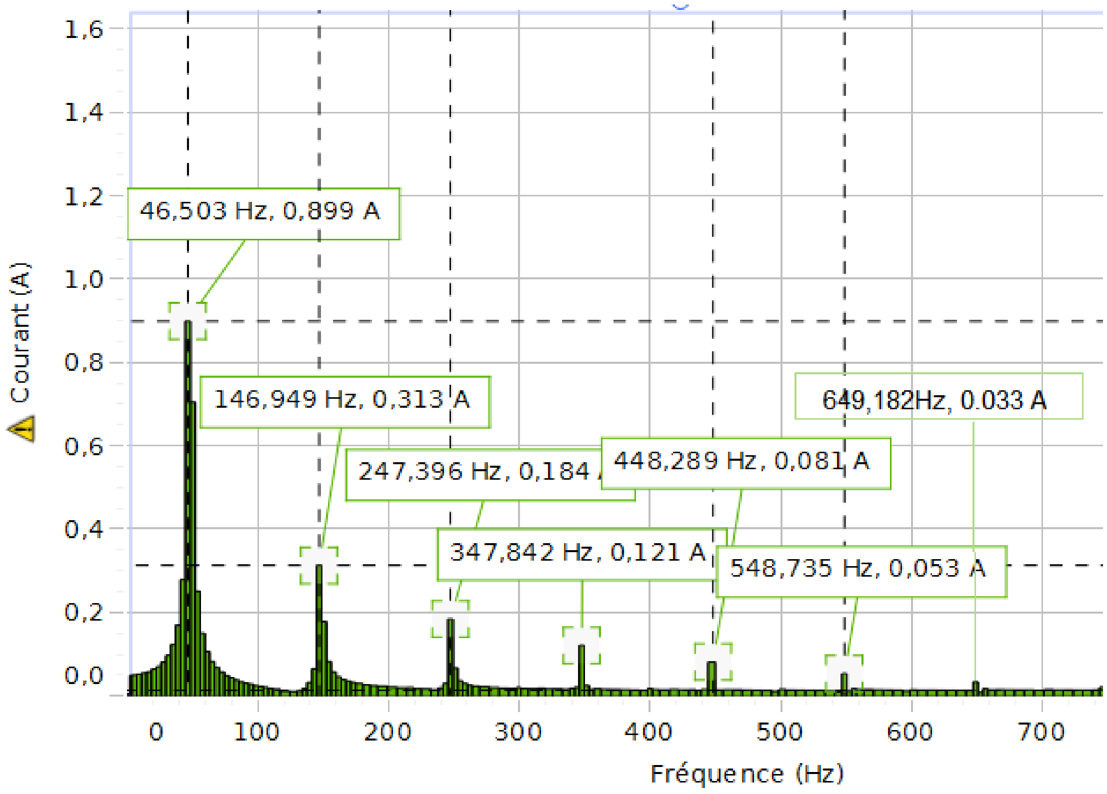


Figure (III.4): Spectrum of the stator current with a stator faults at 0% load (Test 1)

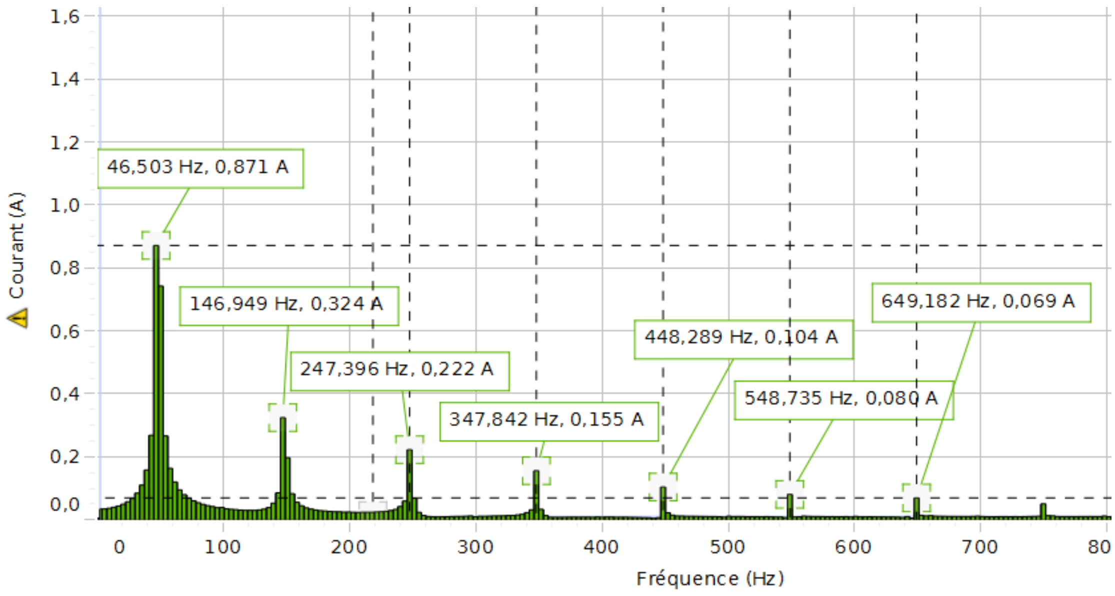


Figure (III.5): Spectrum of the stator current with a stator faults at 15% load (Test 2)

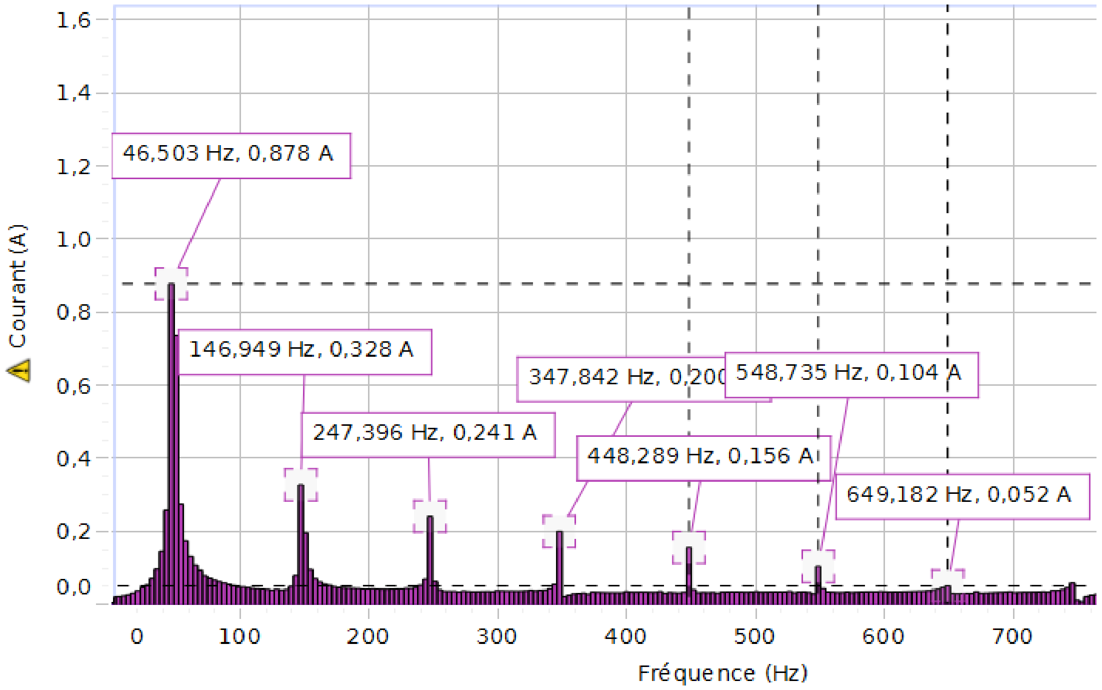


Figure (III.6): Spectrum of the stator current with a stator faults at 45% load (Test 3)

The results of the amplitudes of the different harmonics of the stator current for a faulty motor are recorded in the following table**:**

Table III.2: Amplitudes of different harmonics in the stator current of a faulty motor

Harmonic time range	TH_1	TH_3	TH_5	TH_7	TH_9	TH_{11}	TH_{13}
Frequencies $TH_h = f_s$ (Hz)	50	150	250	350	450	550	650
Amplitudes	A_{Td-1}	A_{Td-3}	A_{Td-5}	A_{Td-7}	A_{Td-9}	A_{Td-11}	A_{Td-13}
A_{Td1} (A) Test 1, At 0% load	0.899	0.313	0.184	0.121	0.081	0.053	0.033
A_{Td2}(A) Test 2, At 15% load	0.871	0.324	0.222	0.155	0.104	0.080	0.069
A_{Td3} (A) Test 3 , At 45% load	0.878	0.328	0.241	0.200	0.156	0.104	0.052

General remarks

From the results obtained, we see that the different harmonics have unstable values in both cases, so that the amplitude of these harmonics sometimes increases in the case of a faulty motor compared to a healthy motor. Below we will present some of the changes we observed at different loads.

Augmentation for harmonic rank

- for low load: 7, 9, 11, 13.
- for medium load: 5, 7, 9 and 11.
- for full load: 5, 7, 9, 11.

Diminution of the amplitude for harmonic rank

- for low load: 3.
- for medium load: 1, 3.
- for full load: 1, 3, 13.

III.3. Calculation of relative sensitivity

To find the harmonic sensitivity we use the following equation:

$$\mathbf{S_r} = \frac{A_{TH_d}}{A_{TH_s}}$$

S_r : Relative sensitivity.

A_{TH_d}: Amplitude of the stator current in fault motor.

A_{TH_s}: Amplitude of the stator current in healthy motor.

The following tables explain this:

Table III.3: relative sensitivity of different motor time harmonics.

Harmonic time range "h"	1	3	5	7	9	11	13
Frequencies (Hz)	50	150	250	350	450	550	650
Amplitudes	S_rT1-1	S_rT1-3	S_rT1-5	S_rT1-7	S_rT1-9	S_rT1-11	S_rT1-13
Amplitude Test 1, At 0% load	1.022	0.966	1.022	1.390	1.5	2.038	1.434
Amplitude Test 1, At 15% load	0.978	0.885	1.037	1.019	1.029	1.269	1.682
Amplitude Test 1, At 45% load	0.977	0.956	1.012	1.162	1.344	1.283	0.787

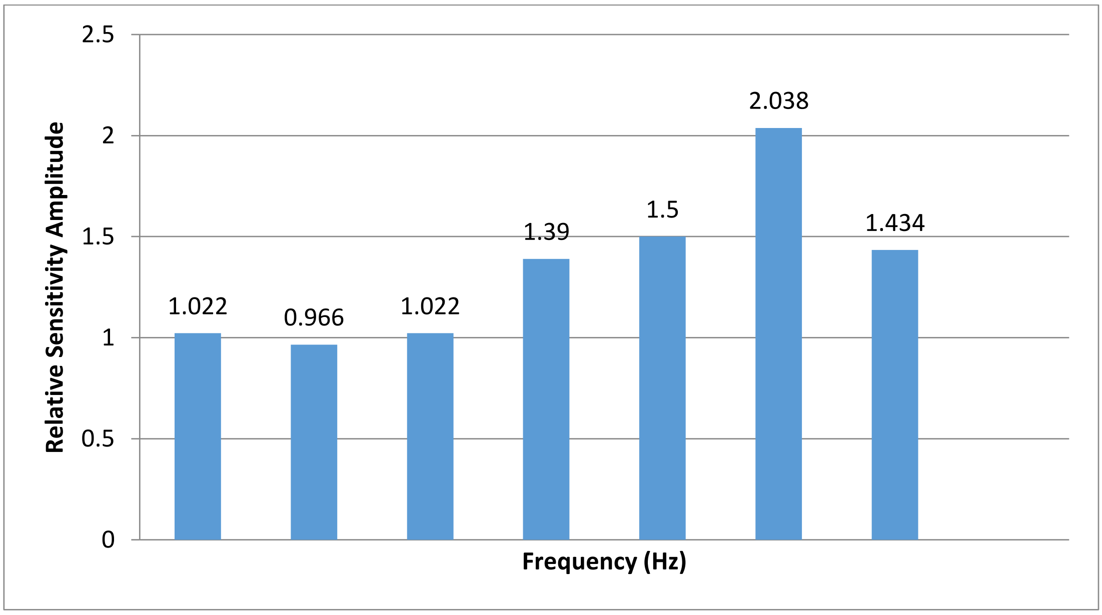


Figure (III.7): Relative sensitivity Test 1 at 0% load.

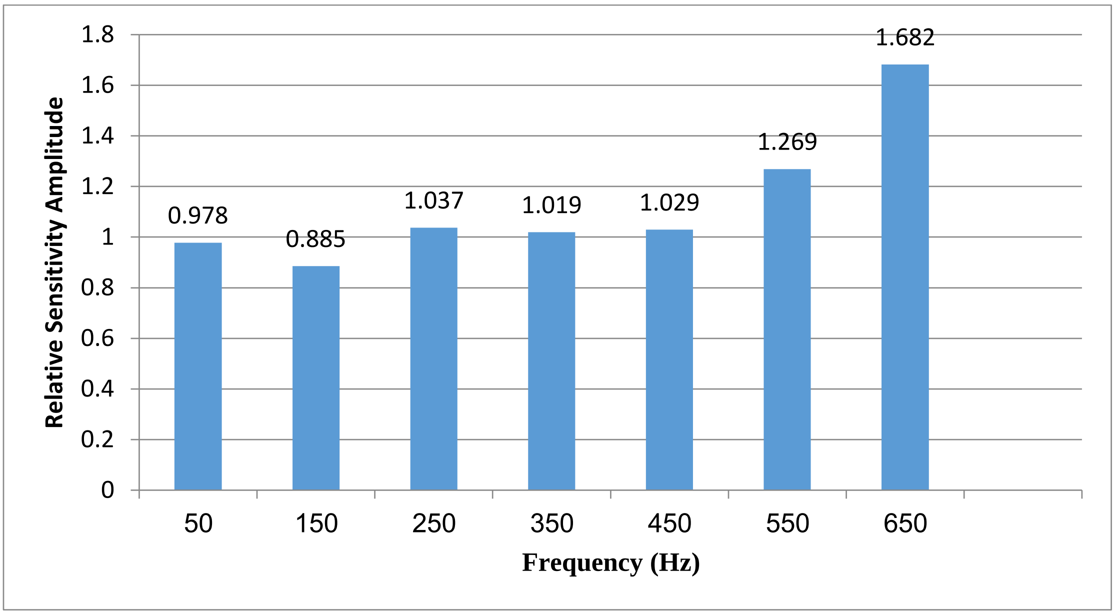


Figure (III.8): Relative sensitivity Test 2 at 15% load.

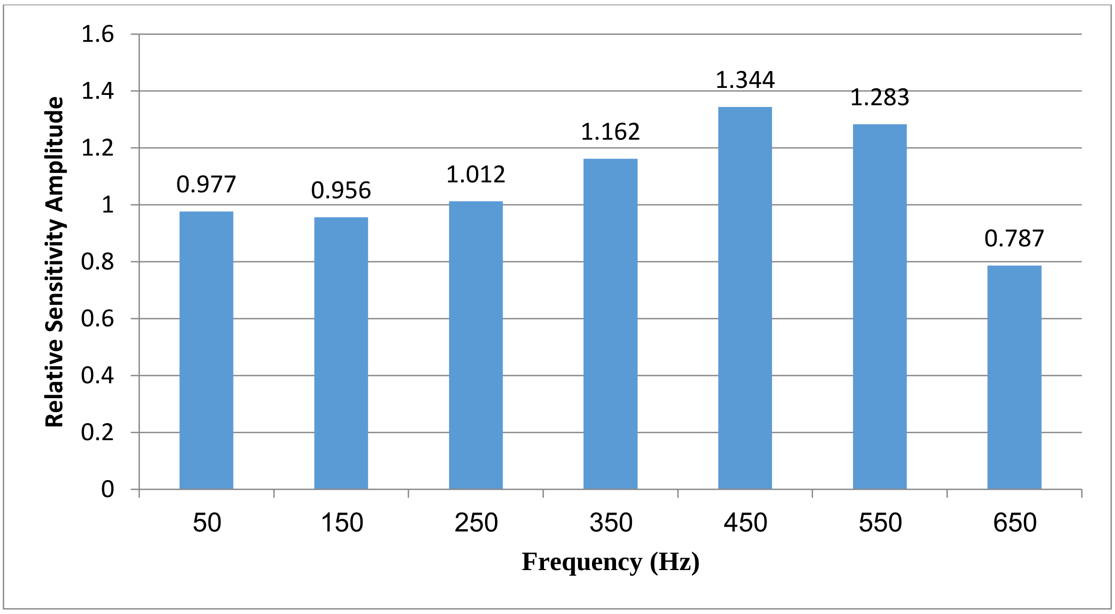


Figure (III.9): Relative sensitivity Test 3 at 45% load.

III.4. Discussion of the results

To analyze and compare the results of the relative sensitivity tests presented, we must examine Figures III.6, III.7 and III.8, which display the relative sensitivity to loads of 0%, 15% and 45% respectively.

Test 1 (0% load) - Figure III.6:

- Relative sensitivity amplitude: varies between 0.966 and 2.038.
- The relative sensitivity peaks at 2.038, showing a large variation in sensitivity according to frequency.

- At 0% load, the relative sensitivity is the most unstable, indicating high response to changes in frequency.

Test 2 (15% load) - Figure III.7:

- Relative sensitivity amplitude: varies between 0.885 and 1.682.

- The relative sensitivity remains relatively stable, with less pronounced fluctuations compared to testing at 0% load, peaking at 1.682.

- At 15% load, stability improves significantly, with a significant reduction in maximum amplitudes.

Test 3 (45% load) - Figure III.8:

- Relative sensitivity amplitude: ranging between 0.787 and 1.344.

- Relative sensitivity is the most stable of the three tests, with amplitudes closest to 1, indicating that increasing load reduces sensitivity variations.

- At 45% of the load, the relative sensitivity becomes more stable, which suggests that increasing the load has a stabilizing effect on the sensitivity.

The results show that increasing the load reduces variations in relative sensitivity in response to frequency changes. This may indicate an improvement in the stability of the tested system under higher loads. This type of analysis is crucial to understanding how the system responds under different load conditions and can help optimize its use based on specific needs.

III.4.1. Relative sensitivity related to different loads and tests for each harmonic range:

The following figures show the development of sensitivity values for the different loads used in the experiment. The loads are 0%, 15%, and 45%, each at a specific frequency.

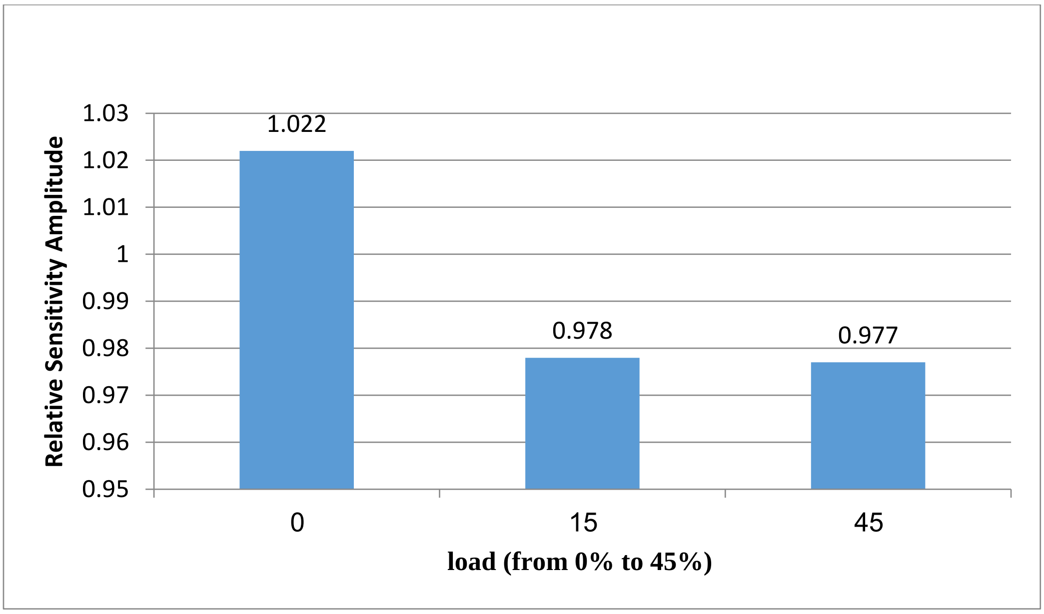


Figure (III.10): Sensitivity relative with TH1=50 Hz.

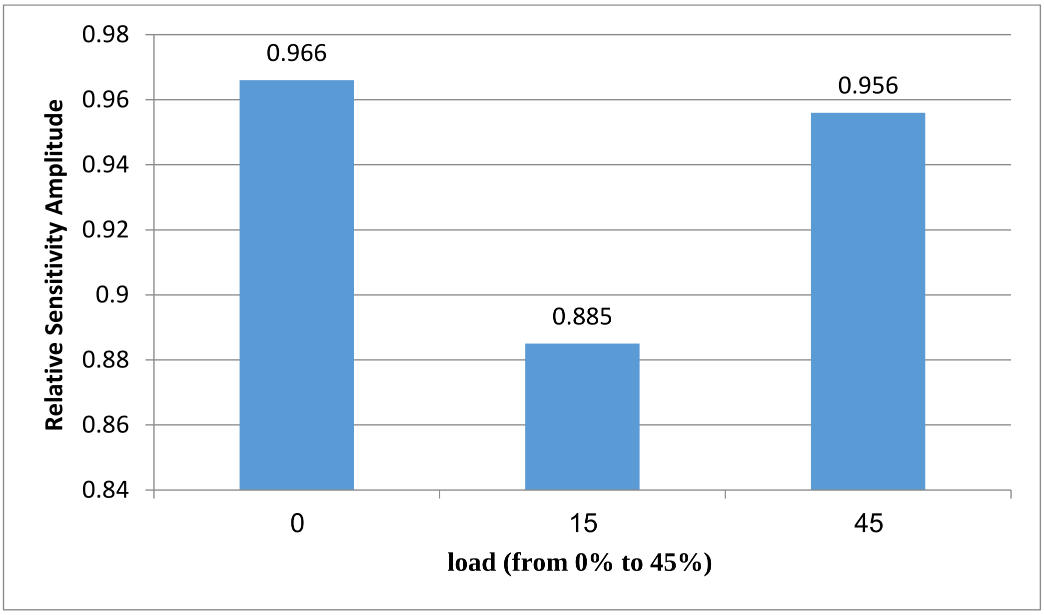


Figure (III.11): Sensitivity relative with TH2=150 Hz.

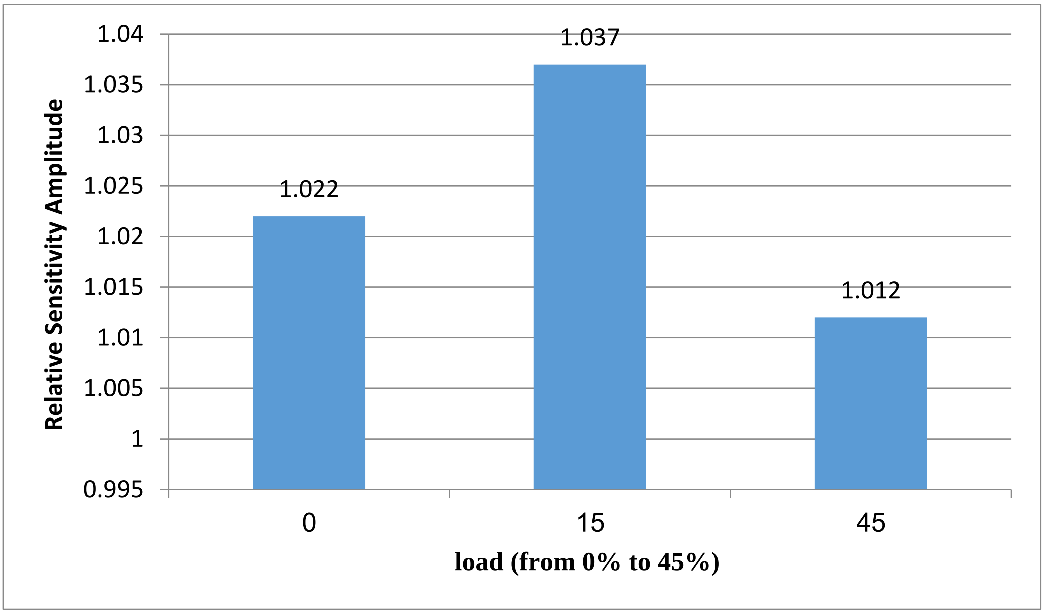


Figure (III.12): Sensitivity relative with TH3=250 Hz.

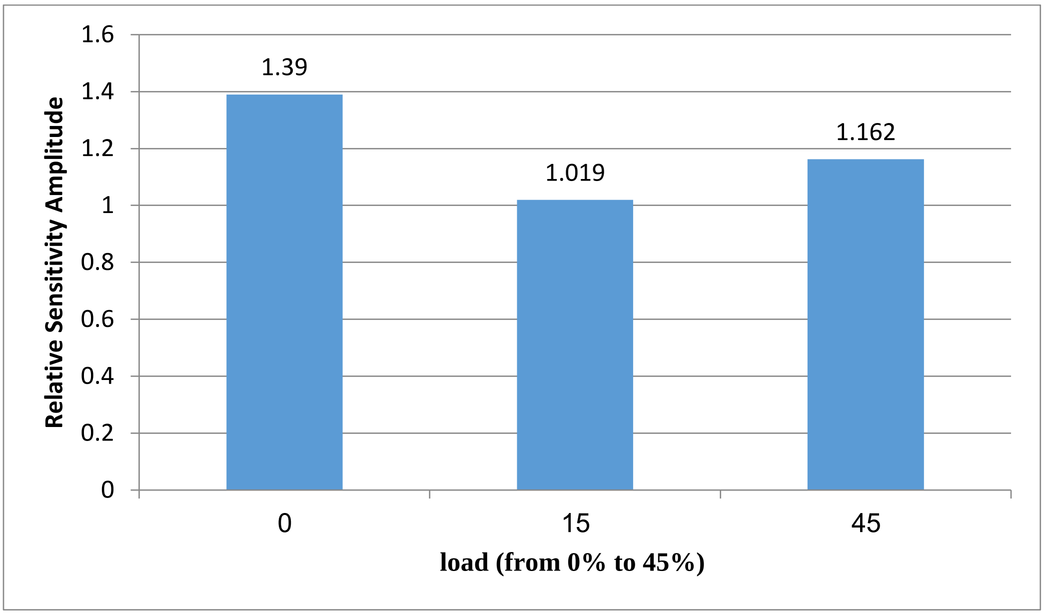


Figure (III.13): Sensitivity relative with TH4=350 Hz.

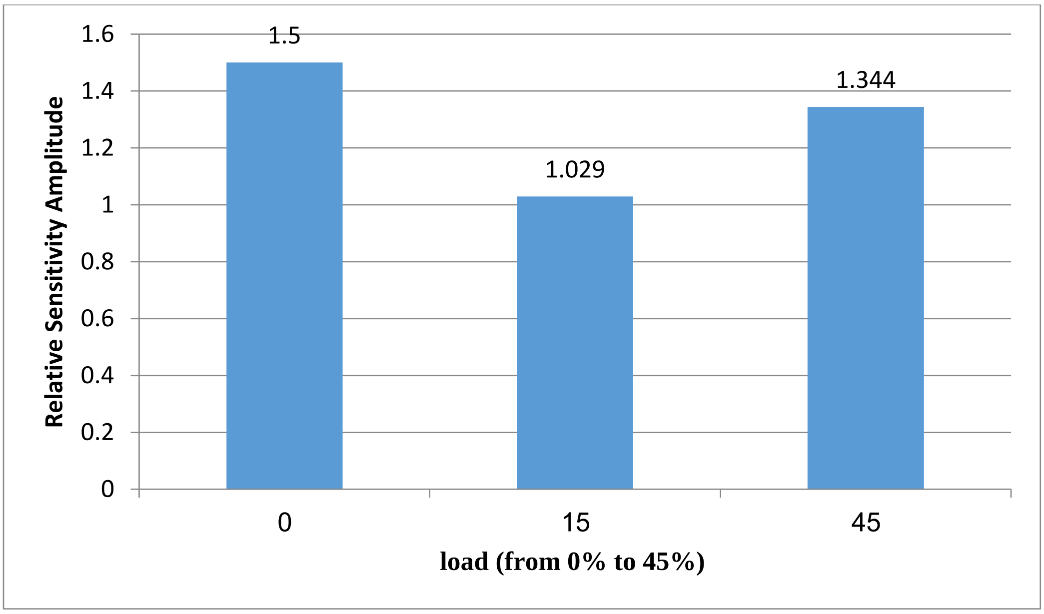


Figure (III.14): Sensitivity relative with TH5=450 Hz.

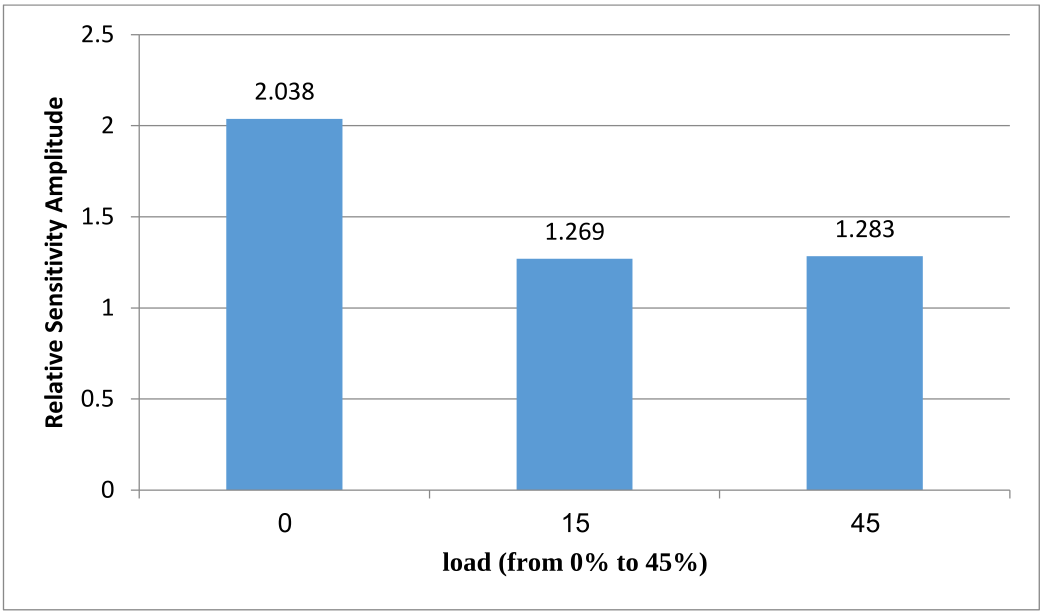


Figure (III.15): Sensitivity relative with TH6=550 Hz.

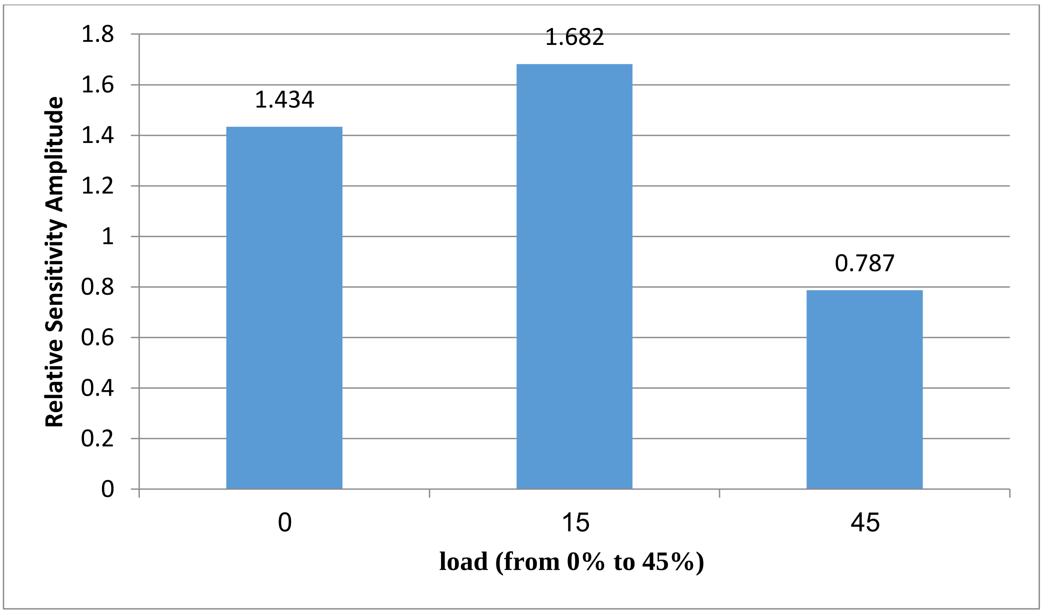


Figure (III.16): Sensitivity relative with TH7=650 Hz.

III.4.2. Calculation of the average sensitivity amplitude

In this step we will calculate the average Amplitude, and through the results obtained mathematically and graphically, we can determine the best time harmonic for detecting stator faults.

$S_{average} = \sum_{k=1}^{3}[S_r] \div 3$

$S_{average}$: average sensitivity amplitude.

S_r: Relative sensitivity.

The following table gives the average sensitivity results for different harmonics of the motor.

Table III.4: average sensitivity of the different motor harmonics.

Harmonic rank "h"	1	3	5	7	9	11	13
Frequency (Hz)	50	150	250	350	450	550	650
$S_{average}$	0.992	0.935	1.023	1.190	1.291	1.53	1.301

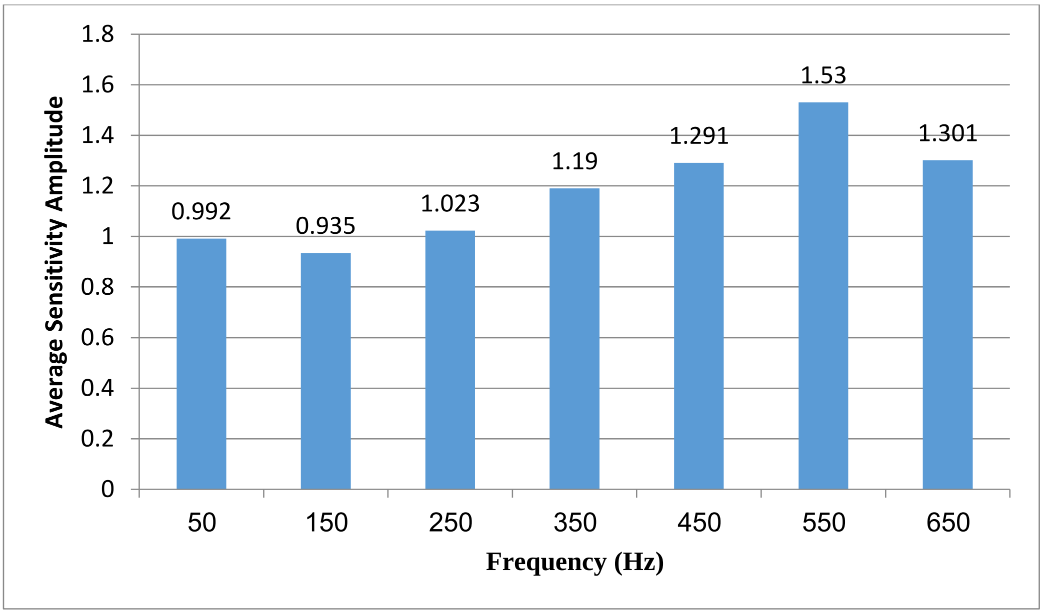


Figure (III.17): Average sensitivity to different time harmonics of the motor.

Note:

We note that Th6 is the best harmonic for detecting stator faults. This harmonic can be used as a diagnostic index for stator faults, as it is the most sensitive among the others. Its high sensitivity allows for predictive diagnosis, helping to prevent material damage and human loss**.**

III.5 Conclusion

In this chapter we studied constant current spectroscopy using a diagnostic model with time harmonics. For spectroscopic analysis, fast Fourier transform (FFT) was used. By studying and analyzing the results obtained through various tests and working conditions of the induction motor. Also by studying amplitude variations and using relative sensitivity as an indicator to identify significant changes. We have found that when the motor is running in condition there are errors in the stator, which leads to significant imbalance. Based on the analysis and comparison of previous experimental results of stator time-current harmonics, we can use TH6 as a diagnostic indicator to detect stator faults. This provides us with proactive diagnosis of electrical machines.

General Conclusion

General conclusion

Due to the wide use of asynchronous motors in many fields, the need for early and rapid fault detection has become essential. This work focuses on fault diagnosis in squirrel cage induction motors.

To begin this study, we revisited a variety of faults that can affect the smooth operation of squirrel-cage three-phase induction motors, focusing on the underlying causes of these faults. By understanding the origins of these problems, we sought to establish a foundation for effective diagnostic approaches. We also comprehensively reviewed the latest monitoring technologies designed specifically for these engines, reviewing the methods and strategies used in the industry to monitor and evaluate their health and performance.

This review aimed to identify and present the most effective and reliable methods available. At the beginning of this work, we also reviewed the general aspects of squirrel-cage design asynchronous motors, and discussed various problems that can affect their performance and their sources, adding depth to our understanding of the importance of monitoring and early diagnosis of faults.

In the second chapter, we presented a method for studying fault diagnosis in induction motors using time harmonics, which is based on analyzing the effect of a short-circuit fault on the performance of the studied induction motor. In the third chapter, we conducted an in-depth experimental study to obtain a comprehensive understanding of the observations resulting from the simulation program (PASCO). We reviewed and discussed the most important diagnostic techniques in detail, including the Fast Fourier Transform (FFT) used to analyze the stator current spectrum, which enables accurate identification and diagnosis of stator faults.

Through this study, we were able to process the current images extracted from the current sensor and visualize the harmonic spectrum using a computer program. We reach an important conclusion based on the results that the sixth harmonic TH6 shows the highest sensitivity for detecting stator faults.

Through this work, we gained valuable hands-on experience performing electric motor analyses, and learned how to use a variety of tools and devices to accurately collect and analyze data. The results we obtain from this work are expected to advance our understanding of motor diagnostics and provide valuable insights for future research and applications in the field of electrical engineering.

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