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In electrics machines

Thesis

Diagnosis of rotor faults induction machines using harmonic

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Dedication

I dedicate this memory to my mother, who always encouraged me to do so

To go on and who gave me all his love to bear

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In memory of my father who passed away seven years ago.

To my brother Karim and my sister Hana, who were always there I.

To my friends with whom I shared the most beautiful moments.

To all who are dear to me, who are close to my heart, and to everyone who love me and share my joy...

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I dedicate this to my mom, dad and my big and small family with whom .I shared the most beautiful moments

To all those dear to me, close to my heart

Who loves me and shares my joy...

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I dedicate this fruit of work:

To my mother and my father who have all the credit

To my brothers (FATIMA ; AYMANE; RANYA ; HAMID ; HAFSA; GHOFRAN. and My uncle's wife: ASMA.

To all friends: GROUPE LAHSSIRA ;GROUPE BERRAHAL; Miloud El-haj Taha rachad Islam Ahmed.b.

To special Person.

To all my colleagues and special regiment

”Electrical machines.“

ATMANE BOUZGAG

Abstract

This study focuses on the diagnosis of rotor faults induction machines using harmonic current analysis. Rotor faults induction machines can lead to performance degradation and unexpected failures. The study utilizes harmonic current analysis as a diagnostic tool to detect and identify rotor faults. Various diagnostic techniques, such as spectral analysis and Fast Fourier Transform (FFT), are employed to analyze the harmonic content of the current waveform. Experimental results and case studies demonstrate the effectiveness of harmonic current analysis in diagnosing different types of rotor faults, such as broken rotor bars or shorted rotor windings. The study highlights the potential of harmonic current analysis as a non-invasive and cost-effective diagnostic technique for detecting rotor faults induction machines , with implications for improved maintenance and performance in industrial applications.

Keyword: Fast Fourier, Diagnostic technique, Harmonic current analysis, induction machines , Broken rotor bars, Experimental results, Transform (FFT).

Résumé:

Cette étude porte sur le diagnostic des défauts de rotor dans les machines asynchrones à l'aide de l'analyse du courant harmonique. Les défauts de rotor dans les machines asynchrones peuvent entraîner une dégradation des performances et des pannes imprévues. L'étude utilise l'analyse du courant harmonique comme outil de diagnostic pour détecter et identifier les défauts de rotor. Diverses techniques de diagnostic, telles que l'analyse spectrale et la transformée de Fourier rapide (FFT), sont utilisées pour analyser le contenu harmonique de la forme d'onde du courant. Les résultats expérimentaux et les études de cas démontrent l'efficacité de l'analyse du courant harmonique dans le diagnostic de différents types de défauts de rotor, tels que les barres de rotor cassées ou les enroulements de rotor court-circuités. L'étude met en évidence le potentiel de l'analyse du courant harmonique en tant que technique de diagnostic non invasive et rentable pour détecter les défauts de rotor dans les machines asynchrones, avec des implications pour une maintenance et des performances améliorées dans les applications industrielles.

Mots-clés : Fourier rapide, Technique de diagnostic, Analyse des courants harmoniques, Machines asynchrones, Barres rotor rompues, Résultats expérimentaux, Transformée (FFT).

ملخص:

تركز هذه الدراسة على تشخيص آلات تحريض أعطال الدوار باستخدام تحليل التيار التوافقي. يمكن أن تؤدي آلات الحث لأعطال الدوار إلى تدهور الأداء والفشل غير المتوقع. تستخدم الدراسة تحليل التيار التوافقي كأداة تشخيصية لاكتشاف وتحديد أعطال الدوار. يتم استخدام تقنيات التشخيص المختلفة ، مثل التحليل الطيفي وتحويل فورييه السريع (FFT) ، لتحليل المحتوى التوافقي لشكل الموجة الحالي. تظهر النتائج التجريبية ودراسات الحالة فاعلية تحليل التيار التوافقي في تشخيص أنواع مختلفة من أخطاء الدوار ، مثل قضبان الدوار المكسورة أو لفات الدوار المختصرة. تسلط الدراسة الضوء على إمكانات تحليل التيار التوافقي كطريقة تشخيص غير جراحية وفعالة من حيث التكلفة للكشف عن آلات تحريض أعطال الدوار ، مع ما يترتب على ذلك من آثار لتحسين الصيانة والأداء في التطبيقات الصناعية..

الكلمات المفتاحية : فورييه السريع ، تقنية التشخيص ، تحليل التيارات التوافقية ، الآلات غير المتزامنة ، القضبان الدوارة المكسورة ، النتائج التجريبية ، التحويل.(FFT)

SUMMARY

Chapter I: Generalities on the induction machine

Chapter II: Experimental results of the statoric current harmonics

Chapter III: Experimental results of the statoric current harmonics

Summary

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LIST OF SYMBOLS

Nr: number of rotor bars.

F.m.m: magneto motive force.

fs: supply frequency [Hz].

P: number of pole pairs.

g: slip.

fexc: eccentricity frequency.

R: number of rotor slots.

DC: Bearing diameter.

IM: Induction machine.

FFT: Fast Fourier Transform.

TGV: Train with big speed.

ANN: Artificial neural networks.

General Introduction

Objectives of different industrial structures are always linked to increasing quality, productivity, and profitability. Relying solely on traditional process monitoring during operation cycles is no longer sufficient.

Currently, diagnosing and detecting faults require significant efforts from researchers in various industrial fields, especially in the case of electric propulsion motors, which increasingly use induction motors due to their power, mechanical operation strength, and cost-effectiveness. However, their use in fixed-speed drive systems is limited compared to variable-speed systems due to the difficulties in controlling them**[1].**

Currently, thanks to advancements in power electronics, effective control of induction motors in terms of torque and speed has become possible. This control opens up wide application areas, such as aviation, nuclear power, chemistry, and rail transportation.

Although the squirrel cage motor is known for its strength among electric motors, various constraints of different natures (thermal, electrical, mechanical, and environmental) can affect its lifespan and lead to faults in the converter and rotor. These faults result in significant economic losses, necessitating the implementation of appropriate monitoring systems**[2]**.

Therefore, it is necessary to implement suitable monitoring systems with the aim of early fault detection. Although they already exist in other fields, spectral analysis, neural networks, and fuzzy logic are considered new techniques in the field of diagnosis.

We wanted to explore the potential contribution of these techniques when applied to the monitoring of a highly nonlinear system, such as the squirrel cage motor. It is evident that it is impossible to cover all the possibilities and configurations in which these techniques can be applied. We will specifically study the problem of fault detection and localization.

This work focuses on monitoring squirrel cage induction motors. We are particularly interested in faults that may occur in the rotor.

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.

The second chapter is dedicated to understanding and diagnosing faults induction machines and analyzing them, specifically the spectral analysis method for current.

The third chapter presents the results of spectral analysis of current in squirrel cage induction motors under different operating conditions, with and without faults, and compares them using Fast Fourier Transform (FFT).

Chapter I:

Generalities on the induction machine

I.1 Introduction

The induction machine is very widespread in the industrial environment because of its robustness and its low cost of manufacture and maintenance. At first, its use was the drive of constant speed systems. Today, with the improvement of power electronics, this supplants DC motors in an area in which they excelled, that of speed variation.

In the industrial environment, maintaining continuity of service requires an effort from the from production operators. The weak link is mainly the machine electricity, because its failure immediately paralyzes production and leads to a loss very important financial. So-called "predictive" maintenance must therefore be provided in order to prevent in time the faults likely to occur in the engines.

In this chapter, we will present some general information on electrical machines, in particular the induction motor.

I.2 History of electrical machines

* In 1821 the Englishman Michael Faraday produced the first electromagnetic motor. The following year Peter Barlow added a cogwheel to it.

* In1831 Faraday stated the principles of electromagnetic induction. During the same period, the Russian Friedrich Emil Lenz and the American Joseph Henry carried out similar work, thus contributing to the discovery and understanding of this phenomenon.

* In 1832 Ampère in collaboration with the French manufacturer Hippolyte Pixii, realized the direct current generator.

* In 1836 the Englishman Hyde Clarke produced a machine whose structure is reversed compared to that of Pixii/Ampère which improved the rectifier switch.

* In 1842 Davidson uses one of the first rotating motors with variable reactance.

* In 1848, Froment engines appeared, with a torque of 500 N.m. These engines were probably the first to be used for industrial applications.

* In 1860 the company "l'Alliance" industrially manufactured generators of complex structures.

* In 1865 the Italian Antonio Paccinotti built a prototype of a direct current machine with ring armature and radial commutator, the operation of which was greatly improved.

* In 1888 Nikola Tesla filed a number of patents for his entire polyphase system (transformers, generators, synchronous and induction motors, etc.). In those years,

a struggle between Edison and Tesla arose over the choice of direct or alternating current for the production and use of electrical energy.

We note in this brief history that researchers and engineers have not stopped improving, developing and inventing other machines, which have satisfied the needs of several industrial and domestic applications, which has given rise to many machines ranging from “micro machines” to “giga machines”.

The possibilities of conditioning electrical energy, offered by power electronics, have not only made it possible to considerably modify the operating conditions of conventional direct current and alternating current machines, but have also led to the development of new machine classes such as DC machines of the brushless type (brushless), etc**[3],[4]**.

I.3 Induction machine

I.3.1 Definition

The induction motor is by far the most widely used motor in all applications industrial, because of its low cost, its small size, its good performance and its excellent reliability.

Its only black point is the reactive energy, always consumed to magnetize the air gap. Machines three-phase, supplied directly from the network, represent the vast majority of applications; supplanting single-phase machines with much lower performance and zero starting torque without artifice.

In the past, its implementation (starting and speed variation) proved to be complicated, but all this has solved thanks to progress in power electronics. The consequence of this development of control electronics means that the induction motor is now used in areas that are very varied: - Transport (TGV east, trams), Industry, Energy production (wind)… **[5]**

I.3.2 IM operating principle

The principle of alternating current motors lies in the use of a field rotating magnetic produced by alternating voltages. The flow of a current in a coil creates a magnetic field. This field is in the axis of the coil; its direction and its intensity are a function of the current. If the current is alternating, the magnetic field varies in direction and direction at the same frequency than the current, if two coils are placed close to each other, the field resulting magnetic field is the vector sum of the other two. In the case of the three-phase motor, the three coils are arranged in the stator at 120° from each other, three fields’ magnets are thus created.

Given the nature of the current on the three-phase network, the three fields are out of phase.

The resulting magnetic field rotates at the same frequency as the current, i.e.,
50 rpm =50 rpm = 3000 rpm

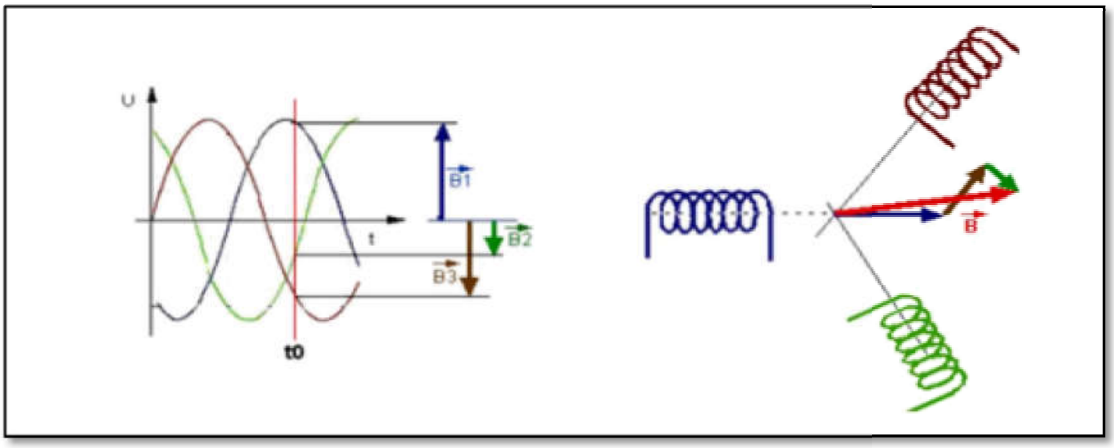

Figure 1.1: Representation of the stator windings **[6]**.

The Three stators' windings therefore create a rotating magnetic field; its frequency of rotation is called synchronism frequency. The rotor is made of aluminum bars embedded in a magnetic circuit. These bars are connected at their end by two conductive rings and constitute a "cage squirrel". This cage is in fact a winding with a large section and very low resistance. This cage is swept by the rotating magnetic field. The conductors are then traversed by induced eddy currents. Currents circulate in the rings formed by the cage; the resulting Laplace forces exert a torque on the rotor. According to Lenz's law the induced currents are opposed by their effects to the cause which gave them birth. The rotor then rotates in the same direction as the field but with a speed slightly lower than the latter's synchronous speed.

The rotor cannot rotate at the same speed as the magnetic field, otherwise the cage will not would be more swept by the rotating field and there would be disappearance of the induced currents and therefore Laplace forces and motor torque. The two rotational frequencies cannot therefore not be synchronous hence the name induction motor. Let us take the example of a motor whose nominal rotational frequency recorded on the nameplate is 2840 rpm, this motor being supplied with a current of 50 Hz, the rotation frequency of the magnetic field is therefore 50 rev/s or 3000 rev/min. The rotor is therefore swept by a magnetic field which rotates at a relative rotational frequency of 3000 - 2840 = 160 rpm**[6]**.

I.3.3 Constitution of the induction machine

The induction IM uses a simple principle of rotating fields which allows it to operation without sliding electrical contacts. This leads to a very robust machine, easy maintenance, which today is very suitable for variable speed applications.

In this program, we limit ourselves to studying the induction machine in motor operation .The latter is composed of a fixed part called "stator" and a rotating part called "rotor".

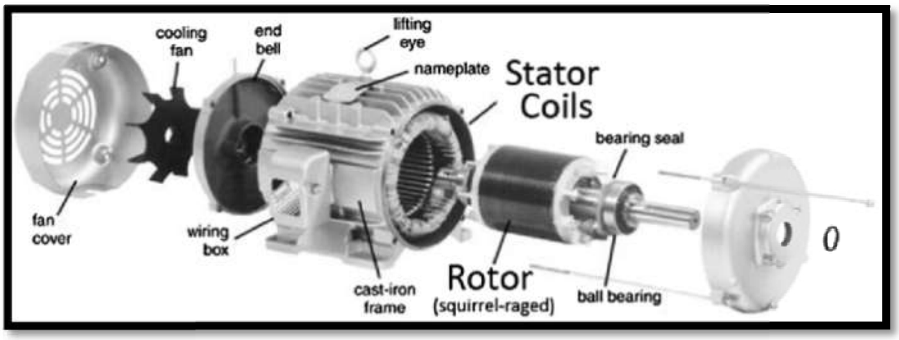

Figure I.2: Example of the squirrel-cage induction machine.

I.3.3.1 Stator

The stator of three-phase induction motors is the same as that of the synchronous motor or the alternator creates the rotating field. It actually has a magnetic circuit completely laminated in the shape of a crown whose inner periphery is notched regularly with a certain number of identical notches. Into these notches come replace the bundles of conductors forming the stator winding.

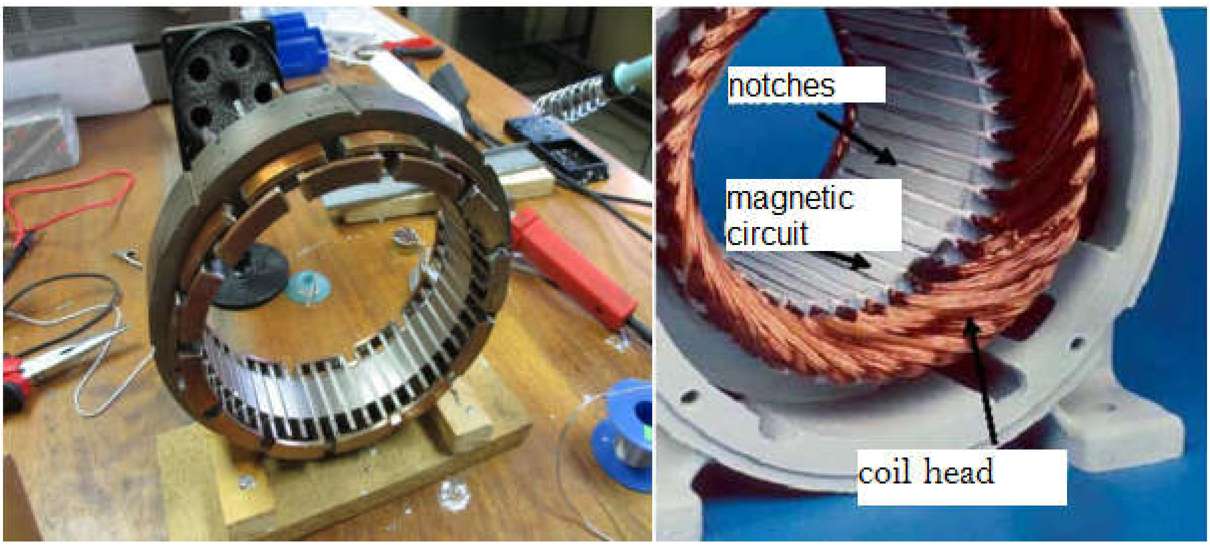

Figure I.3 : Example of IM stator **[7].**

I.3.3.2 Rotor

The rotor is a moving component of an electromagnetic system in the electric motor, electric generator, or alternator. Its rotation is due to the interaction between the windings and magnetic fields which produces a torque around the rotor's axis. There are two types:

a) Wound rotor

The coiled rotor (Figure 1.4) of the machine consists of three coils, each coil is connected to a ring, the rings allow an electrical connection with the coils of the rotor. This type of rotor has been designed to allow variation of the resistance of the rotor by inserting resistors in series with the coils in order to achieve rotor starting. This device then allowed the variation of speed with an acceptable efficiency by means of a process called hypo synchronous cascade. The high cost and appearance of variable frequency drives has made this type of machine obsolete **[8].**

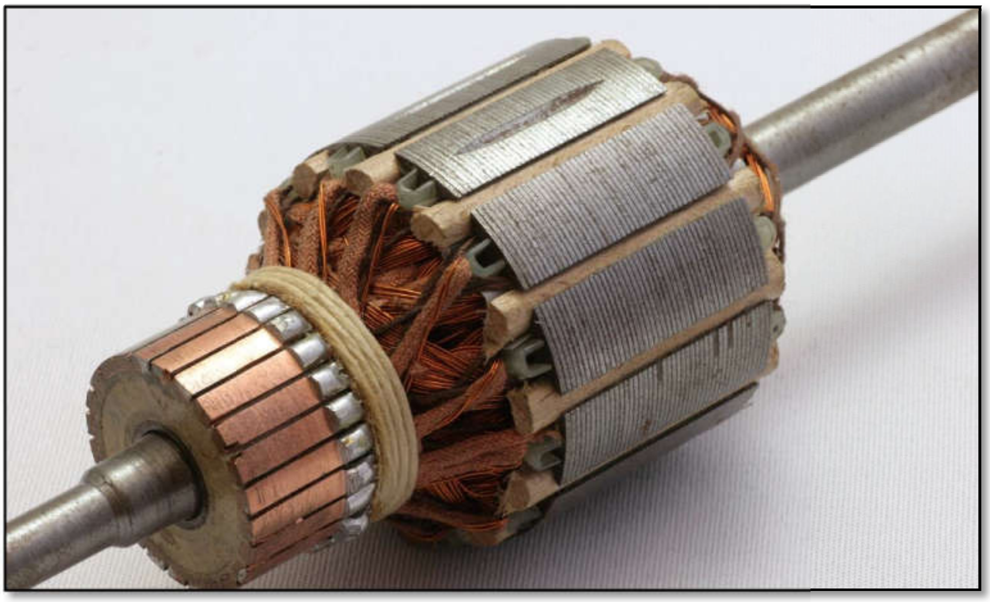

Figure I.4 : Coiled rotor**[9].**

b) Cage rotor

In the cage rotor, the short-circuit rings allow the currents to flow from a lot conductor (rotor bars) to the other. These conductor bars are regularly distributed, and constitute the circuit of the rotor (figure 1.5).

This cage is inserted inside a magnetic circuit consisting of sheet metal discs stacked on the shaft of the machine analogous to that of the wound rotor motor. In the case of squirrel cage rotors, the conductors are made by casting an aluminum alloy, or by solid copper bars preformed and shrunk into the rotor laminations. There is usually no, or very little, insulation between the rotor bars and the magnetic laminations, but their resistance is sufficiently low so that the leakage currents in the laminations are negligible, except when there is a bar failure.

The squirrel cage motor is much simpler to build than the rotor motor wound and, therefore, its cost price is lower. Additionally, it has a greater robustness. It constitutes the largest part of the fleet of induction motors currently in services **[10].**

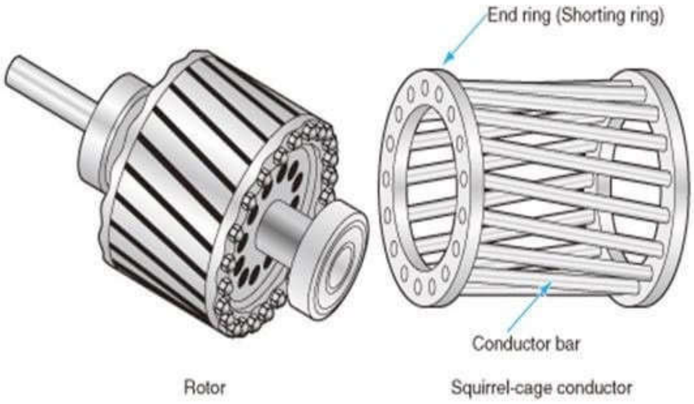

Figure I.5 : squirrel cage rotor of an induction machines.

c) Bearings

Are mechanical components that allow the rotation of the rotor and maintain the different subsets. They consist of two components: the flanges and the ball bearings **[11].**

I.4 Study of the various faults affecting the induction machines

Although the induction machines has the reputation of being robust, it can present as any other electrical machine, electrical or mechanical failures. Our goal is to detect these defects in progress or in the process of appearing **[12].**

Among all the methods used or proposed, it is necessary to take one or more signals for:

- treat them.
- analyze them.
- conclude whether or not there is a failure, with certainty.

I.4.1Causes of defects

For the stator, the effects are mainly due to a problem **[13]**:

- thermal (overload).
- electrical (dielectric).

- mechanical (winding).
- environmental (aggression).

For the rotor, the effects are essentially due to a problem:

- thermal (overload)
- electromagnetic (Force in function B2 (t))
- residual (deformation)
- dynamic (drive shaft)
- mechanical (bearing)
- environmental (aggression)

These faults are distributed according to the following figure:

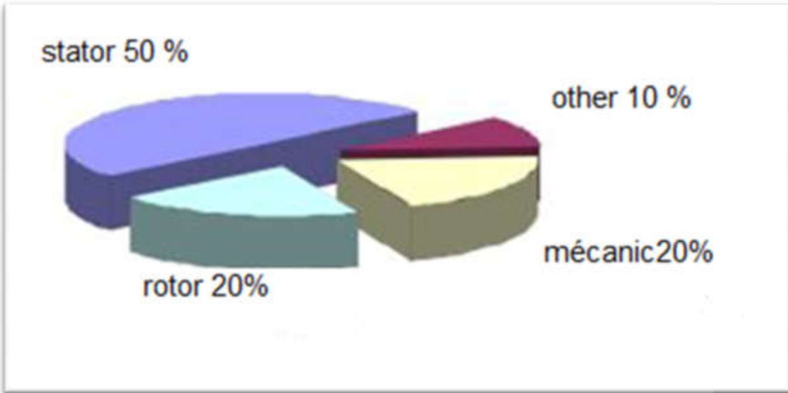

Figure I.6: distribution of faults**[14].**

I.5 Causes of stator and rotor faults

There are many causes of stator and rotor faults, the most common of which are summarized below **[15]**:

***Stator faults**

- -short-circuit between turns: overvoltage, excessive temperature, vibration, humidity
- -short-circuit between phases: high temperature, unbalanced power supply, installation fault;

- -insulation fault: frequent start-up, partial discharge, condition, extreme temperature and humidity.
- -fault between the stator and the casing: thermal cycle, abrasion of the insulation, fouling of the turns by the casing, presence of angular points in the notches, impact.
- -movement of the conductors: frequent starting, coil head vibration.
- -connector failure: excessive vibration.
- -frame vibration: incorrect installation, magnetic imbalance, supply imbalance, overload, movement of the windings, contact with the rotor.

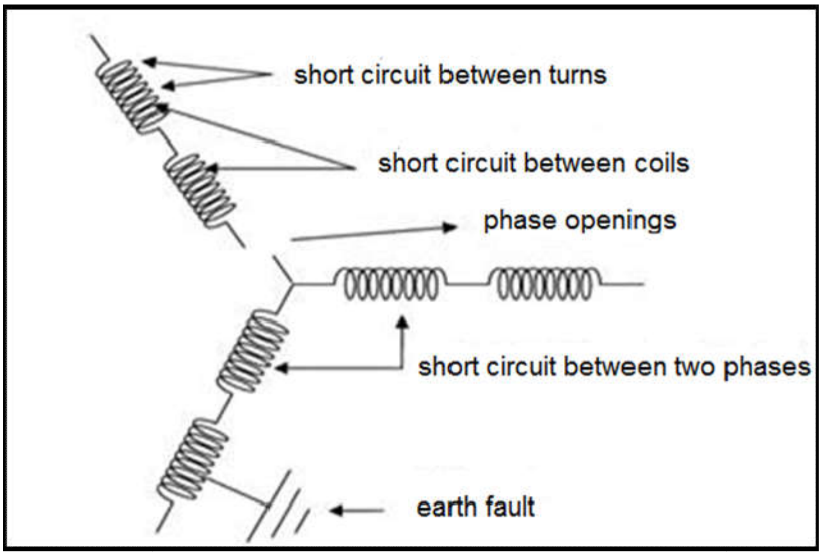

Figure I.7 : Stator faults**[15].**

***Rotor faults**

- Bearing fault: incorrect installation, magnetic imbalance, high temperature, loss of lubricant, unbalanced load, corrosion.
- bar failure: thermal cycle, long-term transient state.
- magnetic imbalance.
- rupture of a ring portion: thermal cycle.
- eccentricity: poor installation, magnetic imbalance, bearing defects.
- bearing misalignment: coupling fault, poor installation, overload.
- magnetic circuit fault: manufacturing fault, overload, thermal cycle.
- mechanical imbalance: misalignment, movement of short-circuit rings.

Statistical studies show us that some failures are more frequent than others, which leads us to focus our study on the most common types of defects. Among the major breakdowns, we find the following:

I.5.1 Stator faults

I.5.1.1Short-circuit between turns

This fault leads to an increase in stator currents in the affected phase, a slight variation in amplitude on the other phases, modifies the power factor and amplifies the currents in the rotor circuit. Short-circuits between turns of the same phase appear either at the level of the coil heads or in the slots **[16].**

I.5.1.2 Short-circuit between phases

This type of failure can occur at any point of the winding; however, their percussions will not be the same depending on the location. This feature makes it difficult an analysis of the impact of this defect on the system.

The appearance of a short-circuit close to the power supply between phases, would induce very high currents which would lead to the melting of the supply conductors and/or the tripping by the protections.

On the other hand, a short-circuit close to the neutral between two phases generates an imbalance without causing the melting of the conductors.

The stator currents are totally unbalanced and this unbalance is proportional to the fault that appears. The currents in the bars as well as in the rings are increased when this fault appears. The detection of this type of fault can base on phase current unbalance **[17].**

I.5.1.3 Insulation faults in a winding

The degradation of the insulators in the windings can cause short circuits, effect, the various losses (Joule, iron, mechanics, etc.) generate thermal phenomena being interpreted by an increase in the temperature of the various components of the engine, and insulation materials have a temperature, voltage and mechanical limit.

Therefore, if the working environment of an insulation material exceeds one of these limits, this material degrades in an accelerated manner, and then ends up no longer ensuring its function, in this case, a short circuit may appear in the winding concerned **[18],[19].**

I.5.1.4 Phase / frame short circuit

The frame generally has a floating potential, but for reasons of mechanical connections, it is often connected to ground. If the potential is floating, a short circuit between the winding and the frame does not matter from the material point of view, except for the capacitive effects, the frame then takes the potential of the winding at the place of the short circuit which can lead to insulation faults in the winding. In addition, this failure will generate a component. On the other hand, in terms of personal safety, this type of fault can be very dangerous and it is then necessary to set up protective devices (differential circuit breakers).

In the presence of this type of failure, the voltage of the phase concerned does not change. However, the current flowing in this phase increases with the reduction of resistance and inductance. This increase in current results in an increase in zero sequence temperature leading to the appearance of a pulsating torque. A measurement of the leakage current could make it possible to detect this type of fault **[20].**

I.5.1.5 Magnetic circuit faults

These defects lead in most cases to an asymmetry at the level of the operation of the machine, which in turn can accentuate the problem by phenomena overheating, overvoltage**[21].**

I.5.2 Rotor faults

I.5.2.1 Bearing faults

The majority of faults in electrical machinery relate to bearing faults which have many causes such as fatigue spelling, lubricant contamination, excessive load or electrical causes such as circulation leakage currents induced by the inverters.

Bearing defects generally cause several mechanical effects in machines such as an increase in noise level and the appearance of vibrations by the movements of the rotor around the longitudinal axis of the machine. This type of fault also induces variations (oscillations) in the load torque of the induction machine. The ultimate point of failed bearings is rotor locking**[22].**

I.5.2.2 Breakage of rotor bars

Rotor bar breakage is a problem of great importance for systems Drive based on induction motors.

This is one of the most frequent rotor faults. The rupture can be located either at level with its notch or at the end which connects it to the rotor ring. Bar fragments broken, thrown at high speed hit the stator windings, causing serious mechanical damage to the insulation of the windings and causes their failure. The deterioration of the bars reduces the average value of the electromagnetic torque and increases the amplitude of the oscillations, which themselves cause oscillations in the speed of rotation, which causes mechanical vibrations and therefore abnormal operation of the machine. There large amplitude of these oscillations accelerates the deterioration of the machine. Thus, the pair decreases significantly with the number of broken bars inducing a cumulative effect of the failure. The effect of a bar break increases rapidly with the number of broken bars.

This defect induces modifications in the stator currents and therefore leads to the appearance characteristic harmonics in the spectrum of this signal. Indeed, when there is a failure of a rupture bus bar, flux harmonics are produced and induce current harmonics in the stator winding at frequencies around the fundamental frequency f_s such that:

$$f_{brc} = f_S\,(1 \pm 2k.g), \qquad k = 1,2,3 \qquad (I.1)$$

g: slip

f_s: stator supply frequency.

I.5.2.3Breakage of portion of ring

Ring portion failure (fig. I.8(b)) is a fault that occurs as frequently as the break of bars. These ruptures are due either to casting bubbles or to differential expansions between the bars and rings. Since it is difficult to detect, this defect is usually grouped, see confused, with the breaking of bars in statistical studies. These portions of rings of short-circuit carry higher currents than those of the Rotoric bars. For this reason, incorrect ring sizing, deterioration of operating conditions(temperature, humidity, etc.) or an overload of torque and therefore of currents, can cause their break. The rupture of a ring portion unbalances the distribution of currents in the rotor bars and therefore generates an amplitude modulation effect on the currents similar to that caused by bar breakage.

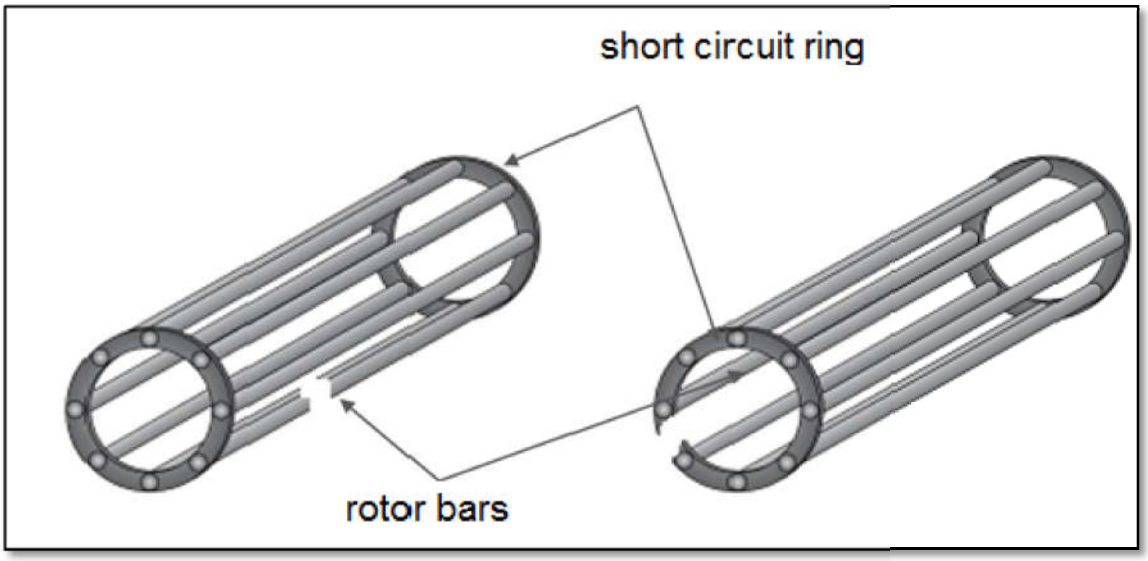

Figure I.8 : Fault in a squirrel cage rotor**[23].**

(a) bar breakage (b) short-circuit ring breakage

I.5.3 Eccentricity

The consequences of mechanical defects are generally manifested at the level of the air gap by eccentricity defects.

The eccentricity of an electric machine is a phenomenon which evolves over time and which exists from its manufacture. This goes through various stages of machining and assembly which induce an offset of the rotor in relation to the stator.

During the operation of the machine, two main causes will aggravate the eccentricity:

- ✓ The first is inherent in the kinematic chain in which the machine intervenes and which can impose a radial force on the shaft of this machine, which will cause wear of the bearings and an amplification of the offset.
- ✓ The second phenomenon that risks aggravating eccentricity is inherent in the operation of the machine; indeed, the offset generates an imbalance in the distribution of the radial forces between the stator and the rotor. The radial force is maximum at the place where the minimum thickness of the air gap is located and will tend to further reduce the value of the minimum air gap and consequently increase even more the imbalance of the radial forces.

The ultimate point of eccentricity is the friction of the stator on the rotor, which is synonymous with rapid destruction of the machine **[24].**

Three categories of eccentricity are generally distinguished **[25]:**

- **Static eccentricity**

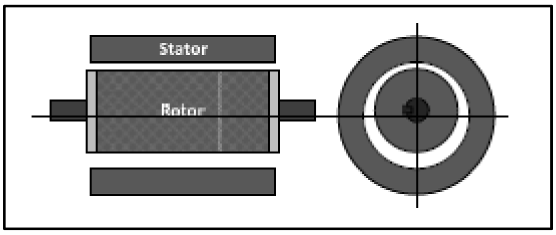

Figure I.9 : Static eccentricity.

Generally due to a misalignment of the axis of rotation of the rotor with respect to the axis of the stator. The main cause is faulty centering of the flanges.

- **Dynamic eccentricity**

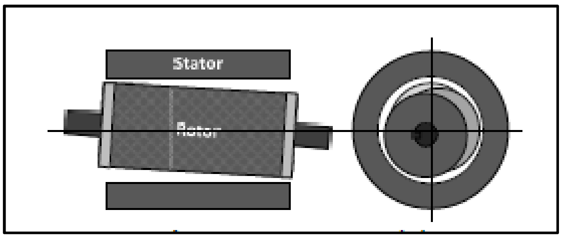

Figure I.10 : Dynamic eccentricity.

It corresponds to a center of rotation of the rotor different from the geometric center of the stator, but, moreover, the center of the rotor rotates around the geometric center of this stator.This type of eccentricity is caused by a deformation of the rotor cylinder, a deformation of the stator cylinder or the deterioration of the ball bearings.

- **The mixed eccentricity**

In reality, static and dynamic eccentricities tend to co-exist. A level inherent static eccentricity always exists, even in manufacturing machines recent. This causes regular uncompensated magnetic attraction efforts in only one direction, and over time this can lead to bending of a shaft and the degradation of bearing ..., all this starting a dynamic eccentricity. Without detection early, the eccentricity becomes large enough to develop radial forces unbalanced which can create friction between the stator and the rotor, which leads to serious machine failure; their frequencies are given by the following frequency components:

$$f_{exc} = f_S \left(1 \pm k.\frac{(1 \quad g)}{p}\right), \qquad k = 1,2,3 \qquad (I.2)$$

Is the sum of the two cases presented above **[26].**

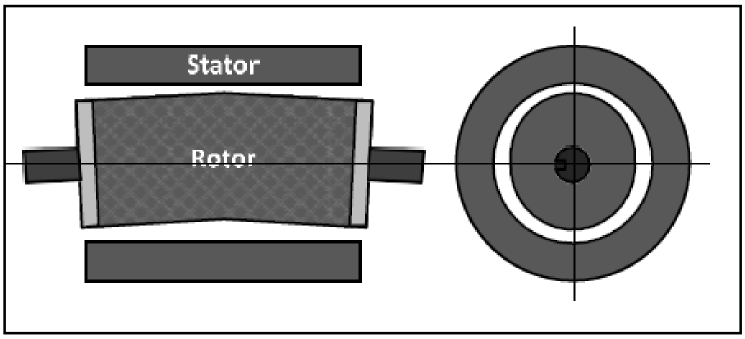

Figure I.11 : Mixed eccentricity

I.6 Conclusion

In this chapter, we presented an overview of electrical machines and highlighted the important faults that can affect induction motors, along with their causes and consequences. Our focus is on studying and detecting broken rotor bars in the cage. Therefore, it is necessary to consider the diagnostic methods used and attempt to find a way to identify and locate the faults, as well as to propose potential repair solutions. This will be discussed in the next chapter.

Chapter II :diagnostics using stator current harmonics

II.1 Introduction

Diagnosing and analysing faults induction machines is a crucial process for ensuring efficient and reliable operation of these machines in industrial settings. Early detection of faults and identifying their causes is vital to increase machine availability, avoid unplanned downtime, and mitigate high maintenance costs. Common faults induction machines include electrical defects. These electrical faults can involve breakage in the stator or rotor short-circuits between turns of the same phase, insulation loss or damage, and rotor cage bar breakage.

The aim of the fault diagnosis and analysis process is to determine the type, location, and cause of the fault. This process typically relies on monitoring performance indicators of the machine such as vibrations, electrical currents, temperature, pressure, speed, and frequency. Operational data is collected from the machine and analyzed using signal analysis techniques and artificial intelligence methods such as artificial neural networks (ANN) and deep learning.

In This chapter will discuss error detection, starting with diagnosis and then analysing them in asynchronous devices.

II.2 Diagnostic

II.2.1 Definition

Diagnostic in asynchronous squirrel cage machines refers to the process of detecting, identifying, and locating potential faults or problems in the machine. These faults or problems may include deviations in the motor operation, phase imbalances, increased load on the motor, excessive rise in motor temperature, insulation faults, rotor faults, bearing faults, electrical disturbances, efficiency loss, and others. Accurate diagnostic is essential to ensure the best possible operation of the squirrel cage induction motor, provide reliability, and achieve a longer motor life. The diagnostic can be performed using various techniques such as vibration analysis, thermal analysis, electrical signal analysis, power analysis, and others.

II.2.2 Diagnostic methods

The diagnostic methods are numerous and varied, corresponding to the diversity of problems encountered. If the decision-making process leads to declaring the process as faulty, it is necessary to choose a diagnostic method. Diagnostic methods can be divided into two main categories:

* Internal methods

* External methods

II.2.2.1Diagnostic using internal methods:

Diagnosing failures using internal methods requires a model of the system being monitored. If such a model is not available, one must be developed that is suitable, reliable, and sufficiently accurate. The model may vary depending on the objectives and can range from aggregated representations to models of normal operation or characteristic operation with specific failures. Typically, a model is a formal (mathematical) description of the system being monitored. Mathematically, multiple models of the same system can exist, similar to those used in control engineering.

A) The model-based method

This method involves comparing the derived variables from a representative model of the functioning of different entities within the process with the directly observed measurements from the industrial process. The presence of a deviation indicates that an anomaly is likely occurring upstream of the modelled module.

B) The utilization of physical or material redundancy

The strategy of physical redundancy involves employing multiple actuators, sensors, processors, and software to measure and/or control a specific variable. A voting principle is applied to the redundant values to determine if a fault is present or not. This approach incurs a significant cost in terms of instrumentation but proves to be extremely reliable and straightforward to implement. It is primarily implemented in high-risk systems such as nuclear power plants or airplanes.

Diagnostic methods utilizing physical redundancy are limited to monitoring the redundant elements (sensors, actuators, etc.) present in an installation. With this technique alone, it will not be possible to detect faults occurring in non-redundant elements. Since its inception, the problem of generating analytical redundancy relations has been the subject of extensive research. These concepts have been further generalized to incorporate temporal redundancy, which involves exploiting the constraints linking different variables within the system. These constraints can often be expressed in the form of analytical relationships connecting known variables (input/output or output/output relationships). These relationships are referred to as analytical redundancy relations. The principle of monitoring involves verifying the algebraic closure of these relationships using online measurements from the system. The concept of analytical redundancy relies on the utilization of a mathematical model of the system being monitored. Consequently, methods employing analytical redundancy for monitoring purposes are referred to as model-based methods. The monitoring principle utilizing a model can be divided into two steps: residual generation and decision-making.

II.2.2.2Diagnostic using external methods

These methods assume that no model is available to describe the cause-and-effect relationships, and the only knowledge relies on human expertise supported by a strong empirical background. In this category, we find all the methods based on artificial intelligence and/or probabilistic approaches.

- **Methods based on Artificial Intelligence (AI)**

In contrast to the various techniques mentioned earlier, in recent years, monitoring and fault detection of electrical machines have shifted away from traditional techniques towards what is known as Artificial Intelligence (AI) techniques**[27].**

Artificial Intelligence (AI) is a branch of computer science that deals with machines reproducing certain aspects of human intelligence, such as learning from past experiences, recognizing complex patterns, and making deductions. Among these methods, we can mention:

- **Diagnostic by Pattern Recognition (PR)**

Pattern recognition techniques have been used to a limited extent so far. A parameter vector, called a shape vector, is extracted from multiple measurements. The adopted decision rules allow classifying the observations described by the shape vector according to the different known operating modes, with and without faults. To classify these observations, it is necessary to be able to provide data for each operating mode. For this purpose, a database must be available, which will then allow constructing the corresponding class for the created fault. Another approach would involve calculating the parameters of the shape vector by performing numerical simulations of the studied machine.

Pattern recognition (PR) is based on classifying o²bjects or shapes by comparing them to template shapes. Generally, two types of PR can be distinguished:

- **Structural (PR)**

It relies on representing shapes using grammars. The structure and arrangement of components in the shape are analyzed to classify it into different classes.

- **Statistical (PR)**

It is based on a numerical representation of shapes. Statistical features such as mean, variance, and correlation coefficients are calculated to describe the shape and classify it.

To apply pattern recognition, the following steps are typically followed:

- Select the parameters that represent the observations, which define the representation space.

- Create a training database.

- Define the different operating modes or classes.

- Build a decision rule that associates a new shape with an operating mode.

- **Diagnostic by Neural Networks**

A neural network is a computational model that is loosely inspired by the functioning of real human neurons. The principle is based on biological neurons, and in order to identify faults in a system, a diagnostic system based on neural networks must have a sufficient number of examples of normal operation and faults to learn from. During the learning phase, the examples are presented to the network as input along with the corresponding diagnostics as output.

The interest of neural networks in the field of diagnostics can be summarized in two points:

The first point is the ability of neural networks to be used as decision rules in an automated diagnostic process.

The second point is their ability to learn and store a large volume of information.

The advantages of neural networks include:

•Speed: They are useful when diagnostics need to be performed in real-time.

•Robustness: Neural networks are robust, especially in the presence of noise.

The main reason for their interest in industrial diagnostics is their ability to learn and store a large volume of information. However, neural networks also have disadvantages, such as:

•Learning can be long and challenging.

•Learning requires significant computational time and needs to be performed on all the data at once, which may cause the network to forget previous results.

•A neural network may not work correctly outside its learning range.

•The major disadvantage is the need to establish a methodology to address inherent problems.

Neural networks have been widely used for diagnosing electrical machines. For example, Ritchie proposed an RBF neural network-based system for fault recognition and classification induction machines . The system extracts characteristic vectors from power spectra of vibration signals to detect electrical and mechanical faults. It can also estimate the severity of detected faults. Similarly, "Filippetti" utilized neural networks for detecting and estimating the number of broken bars in machines.

- **Diagnostic by expert systems**

In general, an expert system is a tool capable of replicating the cognitive mechanisms of an expert in a specific domain. This tool can answer questions by reasoning from known facts and rules. It can serve as a decision support tool, aiding in the diagnosis of industrial systems. The use of expert systems in diagnosis offers the essential benefit and capability of transferring the knowledge acquired by domain specialists to non-experts.

"An expert system is a computer system designed to solve a specific problem by analyzing and representing the knowledge and reasoning of one or more experts in that problem."

- **Diagnostic by Fuzzy Logic**

Fuzzy logic, proposed by L. ZADEH in the 1960s and introduced by GOGUEN in 1969, is presented as a framework for approximate reasoning. It is the logic that governs human mental mechanisms more often than formal logic, as when interpreting an event with uncertainty, logical explanations are often given by exploiting all available rules to approximate the obtained result. In other words, it is the logic that strives to provide solutions to a key problem in practical applications by leveraging the expertise of the operator. Before delving into fuzzy logic reasoning, it is necessary to define its foundations.

Important Note:

The diagnosis is mainly based on the spectral analysis of various signals such as stator currents, torque, vibrations, leakage flux, speed, power, etc., which are the most commonly used approaches to detect mechanical or electrical faults in electric motors. The role of spectral analysis technique is to discover the specific signature of each type of fault. In diagnostics, it is essential to understand how the signatures of different faults manifest themselves, whether it is the appearance of new spectral components (unique fault signature) or only a modification of the amplitudes of existing spectral components. Therefore, it is necessary to have a good knowledge of the different harmonics that appear in the spectrum under normal conditions or in a faulty state. Simulations do not provide real and accurate answers, so we are obliged to visualize experimental spectra to have clear and unambiguous explanations for all pending questions. Additionally, we will conduct comparative studies between different diagnostic methods to determine the approaches that have the highest sensitivity to encountered faults.

II.3 Description of the harmonic phenomenon

Electrical networks and almost all the devices connected to them are subject to numerous disturbances since the arrival on the market of power electronic components such as thyristors, triacs, or high-power transistors.

These components have allowed the development of static converters that regulate and transform electrical energy from one form to another. These converters with respect to the network are seen as being nonlinear loads. They inject harmonic currents into the electrical network. A harmonic is a multiple wave produced by another wave. The latter has amplitude and a frequency. The fundamental frequency used in our electrical networks is 50 Hz. The harmonics have a value corresponding to even or odd multiples of 50Hz. Thus, the frequency of the fifth harmonic is 250Hz (5 x 50Hz). Its amplitude can be measured in volts or amperes. **[28].**

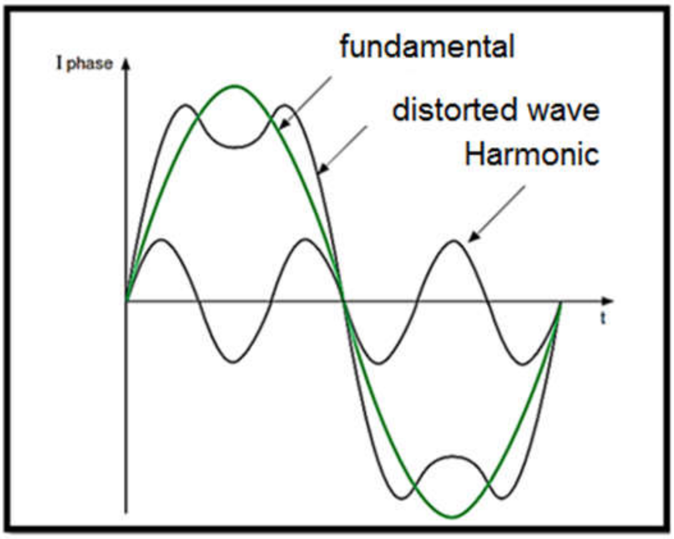

Figure II.12 : Image of a distorted wave**[28].**

II.3.1Origin of harmonics

The following devices are sources of harmonics:

•Static converters based on electronic components (diodes, transistors, etc.) generate harmonic currents **[29],** which affect the power factor. However, it should be noted that symmetrical loads do not generate even-order harmonics. The harmonic spectrum decreases gradually, with the 3rd harmonic being predominant for single-phase loads, reaching up to 80% of the fundamental **[30]:**

•Lighting using discharge lamps and fluorescent tubes generates harmonic currents.

•For AC arc furnaces, the arc is nonlinear, asymmetrical, and unstable. The spectra contain odd and even harmonics, as well as continuous spectrum (background noise at all frequencies). It is worth mentioning that DC arc furnaces are generally powered through rectifiers, and the arc is more stable than in AC current.

•Saturated inductors (as in the case of unloaded transformers subjected to permanent overvoltage) have impedance dependent on the current amplitude flowing through them, causing distortions in this current.

•Rotating machines generate high-order harmonics with negligible amplitudes**[31].**

II.3.2 Causes and consequences of harmonies

II.3.2.1Causes of harmonics

The power electronic devices integrated in the device are the root cause of the harmonics. To power the components DC electronics, the device has a power pack hash with a rectifier at the input that creates harmonic currents. She is, for example, computers, frequency converters, etc. Other consumers cause current distortions due to the way they work. And also produces overtones. These are, for example, the so-called flue recent lamps, discharge lamps, welding machines and devices with an impregnable magnetic core. All loads cause sinusoidal current distortion standards generate harmonics and are called nonlinear loads.

The undesirable effects of harmonics:

Harmonic voltages and currents are superimposed on the fundamental wave bundle their influence on the devices and systems used these dimensions. The harmonics have different effects depending on the receiver:

- or instantaneous effects.
- or long-term consequences of overheating.

II.3.2.2 Instant Effects:

These are the immediate effects on the proper functioning of equipment. He

it's about :

a) Energy losses: Harmonic currents cause in conductors and equipment additional losses by Joule effect.

b) Disruption of weak current lines: Weak current devices are disturbed when used next to of an electrical distribution line with high power. This is the case by example of mobile phones, it is hard to hear.

c) Untimely tripping and plant stoppages: Circuit breakers in an installation are subject to current peaks due to harmonics. These current peaks can cause nuisance tripping, and induce production losses as well as costs related to the time to restart the installation.

d) Vibrations, noises: Harmonica current cause vibrations, acoustic noises, especially in electromagnetic devices (transformers, inductors). Pulsating mechanical torques, due to harmonic rotating fields, will cause vibrations in rotating machinery. They can cause a destruction of the material.

II.3.2.3 Long term effects:

They appear after a long exposure to the phenomenon and result by a partial loss of functionality or complete destruction of the device.

a) Heating, aging: There is a risk of resonance with the upstream circuit (network inductance), following the circulation of certain harmonic ranks. This phenomenon can lead to a current amplification factor in the capacitor causing it to overcharge. And may lead to its breakdown.

b) Temperature rises in conductors and equipment electric: Electrical conductors carry the harmonic currents that produce, by Joule effect, a heating of the conductors in the same way as the fundamental current. Unfortunately, the harmonics do not contribute to the transfer of active power, they only create electrical losses and contribute to the degradation of the power factor of the installation. Capacitors are particularly sensitive to the circulation of harmonic currents because their impedance decreases proportionally to the rank of the harmonics present in the distorted signal.

c) Effects on the neutral conductor: In a balanced system, the homopolar components in the neutral conductor are zero. However, this is not the case in systems with nonlinear loads. In fact, the homopolar currents of the harmonics with multiples of three will add up in the neutral conductor. The intensity of these superimposed currents can seriously damage the neutral cable.

II.3.3 General harmonic solutions

Since harmonics are waves having frequency and an amplitude, the most effective solution is to filter them using passive or active filtration techniques.

II.3.3.1 Passive Filters

Passive filters are designed using passive components such as inductors, capacitors, and resistors to attenuate specific harmonic frequencies. They are typically connected in parallel with the load or equipment generating harmonics. Passive filters can be categorized into different types:

❖ Low-Pass Filters: These filters attenuate high-frequency harmonics while allowing lower-frequency fundamental components to pass through.

❖ High-Pass Filters: High-pass filters allow higher-frequency components to pass while attenuating lower-frequency harmonics.

❖ Band-Pass Filters: These filters allow a specific band of frequencies to pass through while attenuating harmonics outside that band.

❖ Notch Filters: Notch filters are designed to target and attenuate specific harmonic frequencies while allowing other frequencies to pass unaffected.

II.3.3.2 Active Filters

Active filters use power electronic devices, such as thyristors or insulated gate bipolar transistors (IGBTs), along with control systems to actively eliminate harmonics. Active filters generate a compensating current that cancels out the harmonic current, effectively reducing the harmonic distortion. Active filters offer more flexibility and adaptability compared to passive filters. They can be tuned to target specific harmonics and provide dynamic compensation as load conditions change.

II.3.3.3 Hybrid Filters

Hybrid filters combine passive and active filtering techniques to provide enhanced harmonic mitigation. They utilize passive components for filtering specific harmonics and active components for precise control and compensation.

II.3.3.4 Tuned Harmonic Filters

Tuned harmonic filters are designed to attenuate a specific harmonic frequency by introducing a parallel-tuned circuit that creates a low-impedance path at that frequency, effectively diverting the harmonic current away from the power system.

It's worth noting that the selection and design of the appropriate filtering technique depend on factors such as the harmonic frequencies present, the load characteristics, and the desired level of harmonic mitigation. Engineering expertise and careful analysis of the harmonic profile are essential for determining the most effective filtering solution for a specific application.

II.4 General theory on harmonics of the squirrel cage induction machine (SCIM)

The air gap field of an induction motor powered by a sinusoidal current is rich in different harmonics. The analysis shows that these harmonics of the air gap flux which are due to the interactions of the air gap permeance and the harmonics of the magneto motive force f.m.m. It has been shown that rotor slot harmonics “Rotor Rlots Harmonics” (RSH) are generated in the stator current line for a healthy machine at frequencies given by [32].

$$F_{Sh1,2} \ldots (\mathrm{K}) = \left| \left(\frac{KNr(1-s)}{P} \right) Fs \right| (\ ) \qquad \text{(II.1)}$$

We notice that the mathematical expression (II.2) of the direct flow and (II.3) of the indirect flow clearly show that, in addition to the fundamental component, there is also a series of harmonics called rotor slot harmonics of order “h” and at frequencies

$k = 1,2,3 \ldots \quad = 1,3,5 \ldots$

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

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

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

Note also that the derivative of the mathematical expression of the direct flux of the stator (II.2) shows that it will be zero except in the case where "h" belongs to the set "G". For this only the RSH of the order "h", which belong to the set "G", can be detected such that **[33]:**

$$G = \left\{ \left(\quad = \left(\frac{\lambda Nr}{P} \pm 1 \right) \lambda = 1,2,3 \ldots \right) \cap \quad = (6v \pm 1) v = 1,2,3 \ldots \right\} \qquad (II.4)$$

But in the real case, it is very difficult to find a perfectly balanced power source, if not impossible, a well-centred winding as well as an ideally symmetrical geometry. An imbalance in the voltages will cause the creation of negative sequence currents (reverse field) in the stator windings which give rise to other harmonic frequencies in the stator windings. Which gives us, finally, harmonics not only multiple of 3 but odd such as: fs , 3fs ,5fs , 9fs ,….we obtain harmonics whether for healthy or defective operation such as **[32]:**

$$= (2v + 1) \Big| \quad v = 1; 2; 3 \ldots \qquad (II.5)$$

In general, we have two series of harmonics:

1- a series of time harmonics "Time harmonics" (TH) created by the non-asymmetry of the f.m.m with (k = 0) characteristic frequencies **[34], [35]:**

   f_{TH} (h)=hf_s or TH=hf_s (II.6)

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

$$f_{RSH}(\ , k, s) = \left| \left(\quad \pm \frac{k.N_r}{p} (1 \quad s) \right) f_S \right| \quad or \quad S^{\pm} = (\ f_S \pm \ kN_r f_r) \quad (II.7)$$

with *h=1,3,5…*

Thus, we can generalize our study, in the manner done previously, on the natural imbalance of rotor manufacturing which reveals a series of harmonics "Harmonics of Rotor Bar Fault" (RBFH) which resemble those of rotor bar breakage theoretical.

In addition, there is also the natural defect, of static eccentricity and the dynamic one, which produces the mixed eccentricity. This also results in a series of harmonics of mixed eccentricity

"Eccentricity Fault Harmonics" (EFH) **[34] , [35].**

3- A series of Harmonics of Rotor Bar Fault (RBFH) with characteristic frequencies **[35]:**

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

4- A series of mixed Eccentricity Fault Harmonics (EFH) of characteristic frequencies **[32]** :

$f(h,k,s)_{EFH} = \left(h \pm \frac{KNr}{P}(1\ \ \ s)\right) f_s\ or E^{\pm} = hf \pm k$ (II.9)

with $f_r = (\frac{Nr}{P}(1\ \ \ s)f_s$

f_r: is the Rotoric frequency

II.5 Study of the stator current with its harmonics

We will focus our study on phase currents, since this work is essentially based on the analysis of the spectrum of existing harmonics. Thus, we are going to replace the harmonics mentioned above (II.6) -(II.8) in the expressions given by the instantaneous currents circulating in the three phases "a", "b" and "c", of our motor asynchronous. These equations are given by (II.9) **[34], [36]**:

$\hat{I}_{THh}$, $\hat{I}_{s\ k}^{\pm}$,$\hat{I}_{R\ k}^{\pm}$, $\hat{I}_{E\ k}^{\pm}$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,...

$i_{sa}(t)_{sain} = \sum_{h=1}^{m}[\hat{I}TH\ \ \cos(2\pi THt)]\ [+\sum_{h=1}^{n}[\hat{I}s \pm\ \ \cos(2\pi s \pm t) + \hat{I}R \pm k\cos(2\pi R \pm$
$t + \hat{I}_{E}^{\pm}{}_{k}\cos 2\pi E^{\pm}{}_{t}]\ ]$

$i_{sb}(t)_{sain} = \sum_{h=1}^{m}[\hat{I}TH\ \ \cos(2\pi THt\ \ \ (\frac{2\pi}{3})) + \sum_{h=1}^{n}[\hat{I}s \pm\ \ \cos\left(2\pi s \pm t\ \ \ (\frac{2\pi}{3})\right) + \hat{I}R \pm$
${}_{k}\cos 2\pi R^{\pm}{}_{t}\ \ (2\pi 3) + \hat{I}_{E}^{\pm}{}_{k}\cos 2\pi E^{\pm}{}_{t}\ \ (2\pi 3)\ \ ]\ ]$

$i_{sb}(t)_{sain} = \sum_{h=1}^{m}\hat{I}TH\ \ \cos(2\pi THt\ \ \ (\frac{4\pi}{3}))\ [+\sum_{h=1}^{n}\hat{I}s \pm\ \ \cos\left(2\pi s \pm t\ \ \ (\frac{4\pi}{3})\right) + \hat{I}R \pm$
${}_{k}\cos 2\pi R^{\pm}{}_{t}\ \ (4\pi 3) + \hat{I}_{E}^{\pm}{}_{k}\cos 2\pi E^{\pm}{}_{t}\ \ (4\pi 3)$ (II.10)

Types of harmonics	Their characteristic frequencies	Their causes
Time harmonics **(TH):**	$TH = \ f_s$	Imposed by the power source or winding asymmetry
Rotor Slot Harmonics **(RSH)**	$S^{\pm} = \|(\ f_s \pm N_r f_r)\|$	Caused by rotor structure (discrete distribution of rotor bars in rotor slots)
Rotor Bar Fault Harmonics **(RBFH)**	$R^{\pm} = \left\|\left(\ \pm 2ks\right) f_s\right\|$	Due to the asymmetry of the rotor of the rotor cage
Eccentricity Fault Harmonics **(EFH)**	$E^{\pm} = \left\|\left(\ f_s \pm k f_r\right)\right\|$	Due to the natural mixed eccentricity of the rotor

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

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

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

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

In the ideal case, where there is only the fundamental harmonic, the Park vector currents isq (t) andisd (t) in Eqs (II.11) and (II.12) can be simplified as follows [37]

$$I_{sd}(t)_{sain}=\frac{\sqrt{6}}{2}\,\hat{I}_{THh}\sin(2\pi f_s t) \quad \text{(II.13)}$$

$$I_{sq}(t)_{sain}=\frac{\sqrt{6}}{2}\,\hat{I}_{THh}\cos(2\pi f_s t) \quad \text{(II.14)}$$

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

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

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

Now, we will do the experimental visualization of this theory.

II.6 Conclusion

Through fault diagnosis and despite the existence of various mechanisms for analysis and studying the different harmonics of the stator current, it has been found that the time harmonic is the most efficient and simple to use in diagnosis, as it is independent of load variations and other factors. Therefore, we will use it as a diagnostic indicator in the next chapter.

Chapter III: Experimental results of the statoric current harmonics

We, the students **Atmane BOUZEGAG,Ibrahim SLIMANI,Ichrak Badra OUSAMA** attributed this part of the applied work from this thesis to the **Dr. Abd errahim ALLAL .**

General Conclusion

Due to the widespread use of induction motors in various fields, early and rapid detection of faults has become necessary. This work is focused on diagnosing faults in squirrel cage induction motors .

In the beginning of this work, we reviewed the general aspects of motors, especially induction motors with squirrel cage design, and reminded ourselves of the different problems that can affect the performance of these motors and their sources.

In the second chapter, we discussed fault diagnosis and analysis techniques, and familiarized ourselves with the current available methods, particularly spectral analysis of current.

In the third chapter, we presented the most important diagnostic techniques and discussed them, including the Fast Fourier Transform (FFT) used for studying and analyzing the current spectrum in the stator, which distinguishes rotor faults.

Through this work, we gained practical experience in conducting analyses of electric motors and learned how to use various tools and devices to acquire and analyze data. The results obtained from this work will contribute to enhancing our understanding of motor diagnosis and providing valuable insights for future research and applications in the field of electrical engineering.

At the end of this work, we presented a case study on monitoring three-phase squirrel cage induction motors in the event of a fault. This approach is based on previous studies and analysis, and we found that time harmonics increase with the number of broken bars and broken end rings, depending on their relative positions. The results obtained from these methods have demonstrated their ability to diagnose faults compared to the results obtained so far through verification.

Based on this work, we conclude that the harmonics associated with the TH9 frequency are the most sensitive in detecting rotor faults. Our future perspectives revolve around studying diagnosis using artificial intelligence techniques such as neural networks and spectral analysis of current.

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