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Fault Detection in Synchronous Reluctance Machines

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Dedication

I dedicate my Graduation Note to my family and many friends.

A special feeling of gratitude to my loving parents, whose words of encouragement and push for tenacity ring in my ears .

I also dedicate this Graduation Note to my brothers and friends To everyone who supported me throughout my career with material and moral giving and gave me hope .

TELHIG El Walid

Dedication

For my mother who is dear to my heart

*No matter what I do or say, I won't be able to thank and
praise you enough.*

*You supported me with your words that gave me strength
and your prayers that I received and opened all my doors*

So I overcame all obstacles

For my dear father and my role model

*He always encourages me to insist and do more to reach the
desired goal, yes, the bond was mine*

*To everyone who is close to my heart who wish me success
and success in my work*

Especially my brothers and friends

*To everyone who supported me throughout my career with
material and moral giving and gave me hope, a sincere
heartfelt greeting to each of me*

AD Boubaker

Dedication

To my dear mother

*No matter what I do or say, I can never properly thank
you.*

To my dear father

*You have always been by my side supporting and
encouraging me.*

To my dear brother, sister and nieces

And everyone who taught me a letter

To everyone who supported me and gave me love and hope

*And to everyone who wished me well, my family, friends
and colleagues.*

MAMOR J Nadhir

Dedication

For my very dear mother

No matter what I do or say, I won't be able to thank you properly.

Your affection covers me, your benevolence is a guide and being by my side has always been my source of strength to face various obstacles.

To my very dear father

You have always been by my side supporting and encouraging me.

For the soul of my dear grandmother. For those who wish me well

Dear brothers, dear to my heart, and to all who have taught me a message

To everyone who supported me and gave me love and hope

And to everyone who wished me Well, my family, friends and colleagues

I ask God to protect you and enlighten your path

Hammi fathi

ملخص

في العقد الماضي ، ازداد الاتجاه نحو كفاءة أعلى وآلات كهربائية ذات كثافة عزم دوران أعلى بدون مغناطيس دائم للقطاع الصناعي بسرعة ، من بين هذه الآلات ، نميز المحرك المتزامن ذو الممانعة الذي يتميز بالعديد من المزايا مقارنة بالأنواع الأخرى من المحركات ، بما في ذلك الكفاءة العالية والتكلفة المنخفضة والموثوقية وانخفاض في الضوضاء ومتطلبات صيانة أقل .

يمكن للمحرك المتزامن التعرض لأي خلل في أي وقت و بسبب ذلك خسائر كثيرة لذا فإن عملية تشخيص العيوب قبل ان تتحول الى عطب في وقت مبكر أصبح أمرا ضروريا.

علاوة على ذلك ، في مجال التشخيص والمراقبة للأضرار ، هناك العديد من الطرق للكشف عن الأضرار في الآلات المتزامنة و من بين هذه الطرق : طريقة تحليل الاشارة بواسطة تحويل فورييه.

الغرض من هذا العمل هو المساهمة في التشخيص والمراقبة لاكتشاف الأخطاء التي تتعرض لها هذه الماكينة الكهربائية. لذا حاولنا في هذه الدراسة تشخيص عيب الماس الكهربائي لكل من تيارات الجزء الثابت و طريقة شعاع بارك و نهج القوة النشطة والمتفاعلة بطريقة تحليل الاشارة من اجل الوصول الى كشف العيب بأكثر دقة.

الكلمات المفتاحية : المحرك المتزامن ذو الممانعة ، تشخيص ، تحويلات فورييه ، طريقة تحليل الاشارة ، نهج القوة النشطة والمتفاعلة، نهج متجه بارك، تيارات الجزء الثابت .

Abstract

In the past decade, the trend towards higher efficiency and higher torque density electric machines without permanent magnets for the industrial sector has increased rapidly, among these machines we distinguish synchronous Reluctance machines which have many advantages over other types of motors, including high efficiency and low cost , reliability, low noise and low maintenance requirements.

The latter can be exposed to any defect at any time, and this causes many losses, so the process of diagnosing defects before they turn into damage at an early stage has become necessary.

Moreover, in the field of diagnosis and monitoring of damages, there are many methods for detecting faults in synchronous machines and among these methods: The method of signal analysis by Fourier transform.

The purpose of this work is to contribute to the diagnosis and monitoring to detect faults to which this electrical machine is exposed. Therefore, in this study, we tried to diagnose the electrical short circuit defect for each of the stator currents, the Park vector approach, and the active and reactive force approach using the signal analysis method in order to reach the defect detection more accurately .

Key words : Synchronous Reluctance machines (SynRM) , diagnosis , Fourier Transform (FFT) , Stator Currents , Extended Park Vector Approach , Power active and reactive , Signal Based Approaches.

Résumé

Au cours de la dernière décennie, la tendance vers des machines électriques à plus haut rendement et à plus haute densité de couple sans aimants permanents pour le secteur industriel s'est rapidement accrue, parmi ces machines on distingue les machines synchrones à réluctance qui présentent de nombreux avantages par rapport aux autres types de moteurs, notamment à haut rendement et à faible fiabilité des coûts, faible niveau sonore et faibles exigences de maintenance.

Ce dernier peut être exposé à n'importe quel défaut à tout moment, ce qui entraîne de nombreuses pertes, de sorte que le processus de diagnostic des défauts avant qu'ils ne se transforment en dommages à un stade précoce est devenu nécessaire.

Par ailleurs, dans le domaine du diagnostic et de la surveillance des avaries, il existe de nombreuses méthodes de détection des avaries dans les machines synchrones et parmi ces méthodes : La méthode d'analyse du signal par transformée de Fourier.

Le but de ce travail est de contribuer au diagnostic et à la surveillance pour détecter les défauts auxquels cette machine électrique est exposée. Par conséquent, dans cette étude, nous avons essayé de diagnostiquer le défaut de court-circuit électrique pour chacun des courants de stator, l'approche du vecteur de Park et l'approche de la force active et réactive en utilisant la méthode d'analyse du signal afin d'atteindre la détection de défaut avec plus de précision.

Mots clés : Machines à réluctance synchrone (SynRM) , diagnostic , Transformée de Fourier (FFT) , Courants statoriques , L'approche des vecteurs étendus de Park , Puissance active et réactive , Approches basées sur le signal.

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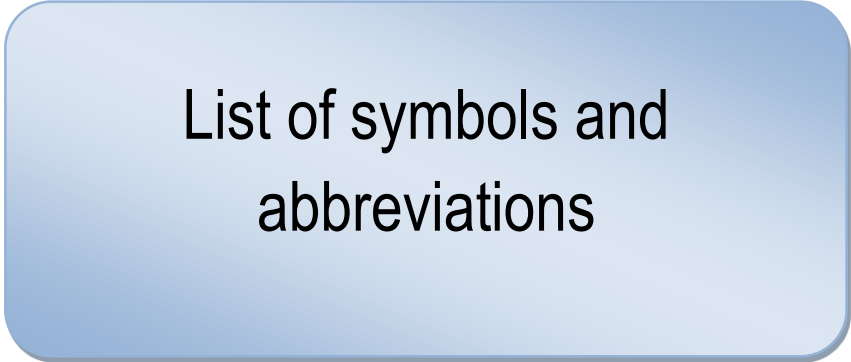
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List of symbols and
abbreviations

List of symbols and abbreviations

SynRM	:	Synchronous Reluctance Motors.
PMs	:	Permanent Magnets .
VSDs	:	Variable-Speed Drives.
SP	:	Salient Pole.
ALA	:	Axially laminated Anisotropy.
TLA	:	Transversally laminated anisotropic.
IM	:	Induction Motor.
MMF	:	Magneto motive Force.
PMSM	:	Permanent Magnet Synchronous Motor.
EPRI	:	The Electric Power Research Institute.
ITSCF	:	Inter-Turn Short Circuit Faults.
FFT	:	Fast Fourier Transform.
MCSA	:	Motor Current Signature Analysis.
DFT	:	Discrete Fourier Transform.
PMA	:	Permanent Magnet Aided.
EPVA	:	Extended Park's Vector Approach.
CWT	:	Continuous Wavelet Transform.
P	:	Power Active.
Q	:	Power Reactive.
V_d	:	The Phase Voltage in d axis.
V_q	:	The Phase Voltage in q axis.
I_d	:	The Stator current in d axis .
I_q	:	The Stator current in q axis.
f_s	:	Frequency of the power supply.
K	:	Positive integer.
z	:	The number of stator slots.
p	:	The number of pole pairs.

List of symbols and abbreviations

- R_f** : The Resistance That Models The Insulation Failure.
- I_f** : The Current in The Short Circuit.
- μ : n/N** n : is equal to short-circuited inter-turns.
 N: The Total number of turns in each phase.

General introduction

General introduction

The Synchronous reluctance motor is a high-efficiency alternative to the induction motor in recent years.

It is a more recent motor solution with interesting advantages such as low rotor inertia, a high power-to-weight ratio, good acceleration performance, flux weakening operation, low material costs, and ease of manufacturing.

The latter uses the frequency characteristic of the iron to rotate the motor. The magnetic frequency (reluctance) is defined as the opposition provided by the magnetic circuit to the magnetic flux (Φ). When a piece of ferromagnetic material is located in a magnetic field, a force is exerted on the material, tending to align the material with an additional coil to produce a synchronously rotating magnetic field.

This frequency drive includes both a stator and a rotor with multiple projections ; the stator poles are wound with windings that are energized, while the rotor's magnetically permeable electric steel plates store magnetic energy by refraining from taking advantage of the tendency of the magnetic flux to follow the path of least magnetization in order to repeatedly align the rotor and stator poles.

The SynRM process depends on the frequency torque, which depends on the Pro Line, which is defined as the ratio between the inductance in the direct and squared axes. Synchronous frequency drives are designed to operate at precise "synchronous" speeds.

The motors are fed by a variable speed motor that implements appropriate control algorithms to increase torque and engine efficiency.

After this definition about the synchronous motor input, we will explain and clarify about this machine in this note .

Chapter I

Generalities on SynRM Faults and the different control techniques

I.1. Introduction:

In recent years, there is a growing interest for high efficiency electric motors without, or with reduced content of permanent magnets (PMs). SynRM is one of the most promising candidates [1]. Latest developments in motor design have provided manufacturers the possibilities to improve energy efficiency, utilize less rare-earth materials, and reduce material and manufacturing process costs. A life cycle analysis of electrical motor-drive systems in [2] gives detailed research on synchronous reluctance motors (SynRM). This study demonstrates that SynRMs are competitive at the consumption stage and efficient at the recycling stage, starting with the acquisition of materials and proceeding through manufacturing, transportation, and marketing. Due to the lack of rare-earth elements, cheap cost, equivalent constant-power speed range, maximum torque per ampere, and efficiency of SynRMs, these motors have become an attractive choice in traction [3][4] and more electrical aircraft applications [5][6]. Furthermore, SynRM can satisfy the demands for highly efficient motors in centrifugal machines, conveyor systems, fans and pumps, cranes, compressors, elevators, crushers, and general machine building (winders, extruders, and servo pumps) [7][8][9]. Despite the fact that SynRMs have existed for almost a century, they have lately received a lot of attention as a result of the growth of power-electronic devices. Leading manufacturers like SIEMENS and ABB have launched newly designed SynRM drive systems in recent decades [9][10]. On the other hand, variable-speed drives (VSDs) provide very efficient motor drives, especially while operating at partial-load conditions and at high speeds [11][12]. Additionally, since this SynRM has received significant attention in industrial applications in recent decades, early detection of faults in this type of machine has become an economic issue as well as a concern for researchers [13]. The opening, short-circuit of one or more turns of the stator phase windings [14] eccentricity, static or dynamic air gap irregularities [15], are among the various faults that might impact the SynRM on the stator and rotor sides. In this chapter, we will first discuss some historical concepts related to Synchronous Reluctance Machines, as well as definitions, concepts, and SynRM Rotor Structures. Then, in the industry, notions of failure monitoring are provided. The most frequent faults that can occur in the SynRM are described, along with their size and influence on machine operation. Following that, a summary of the different diagnostic methods and techniques most commonly used for fault detection is provided, such as the signal approach, the model approach, hardware-based approaches, and artificial intelligence-based techniques. Finally, a brief theoretical review of SynRM control techniques is provided.

I.2. History of the Synchronous Reluctance Machine:

Synchronous frequency machine (SynRM) is based on an old concept, initially described by Kostko in 1923 [16] but due to its low efficiency and poor torque characteristics, it was not invented for industrial purposes. These machines have found application mainly as drivers for discs, tapes and print heads. Interest in synchronous frequency machines having the same stator structure as the induction machine dates back to the 1960's .

SynRM is an induction motor with the same stator as other induction motors, but with a different rotor design. It has a strong load capacity, The rotor design of SynRM lacking bars and magnets leads to cold rotor operation. As a result, SynRM has praiseworthy load ability, particularly at lower speeds [17] allowing it to be loaded up to 2.5 times higher than the nominal torque [10], and can be reached for a short period before a cold start. However, it has some major drawbacks, such as high torque ripple, low energy density, low power factor, and low field weak area [18]. In and with increasing requirements for saving of electrical energy this machine had become more interesting for industrial manufacturers. Conventional induction motors are still one of the least expensive industrial machines, but their further development is quite challenging.

I.2.1 SynRM Rotor Structures:

There are three main types of synchronous reluctance machine rotors. The brief description of their historical development can be found in [19]. The first one is rotor with salient poles. However, these rotors have poor properties to make them competitive in comparison with other alternative rotors. The second type of structure is axially laminated rotor. The rotor is formed from metal sheets which are shaped to create poles after assembling. These sheets are isolated from each other with suitable insulating material. The entire stack is then fixed to the inner part of the rotor, which is mounted on the shaft.

The disadvantage of this solution is its technological difficulties in manufacture. Design and analysis of synchronous reluctance machine that uses this type of rotor is discussed in [20] and [21]. The last main type is transversely-laminated rotor. Air barriers cutted in rotor sheets include a narrow bridge that guarantee the mechanical strength of the rotor. The air barrier may be filled by epoxy to increase the mechanical strength of the rotor. Many papers deal with design of this kind of rotor geometry for example [22][23][24][25] as shown in Fig. I.1.

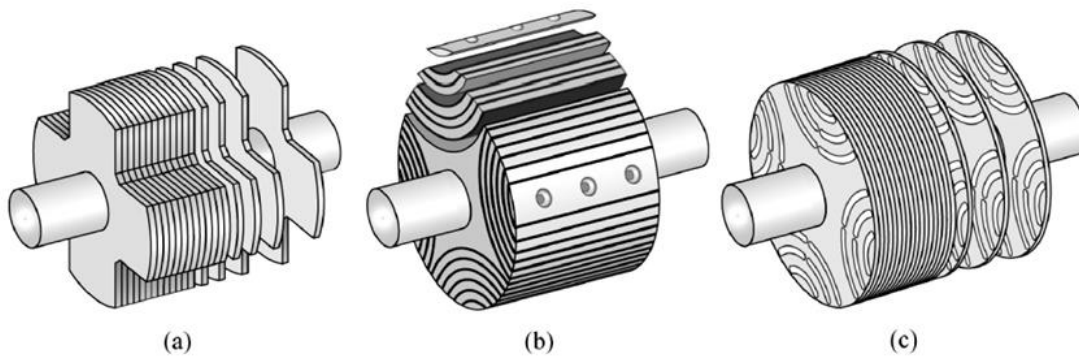


Fig. I.1. Possible rotor design for a SynRM: (a) Simple salient pole (SP) rotor, (b) Axially laminated anisotropy (ALA) rotor, (c) Transversally laminated anisotropic (TLA) rotor [26]

I.2.2. Concept of reluctance :

The operation of the SynRM engine is based on two basic principles:

-Reluctance effect.

-The use of the rotary sinusoidal magnetic force produced by the stator of a three-phase induction type machine [27]

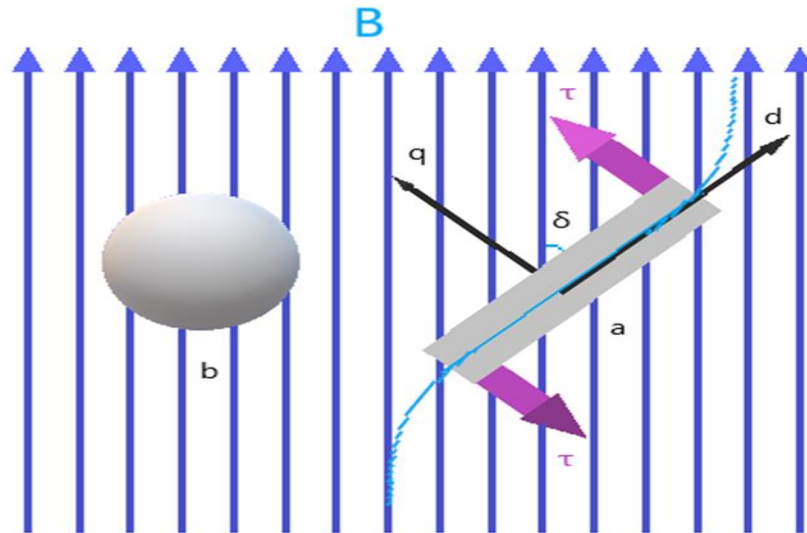


Figure. I.2. shows two objects in a magnetic field B (a) isotope geometry (b) anisotrope geometry[28]

The idea of impedance is shown in Figure 1. We subject magnets (a and b) that are distinct from each other to a magnetic field (B). Considering that magnet (a) is anisotropic, we may see the reluctance difference on the d and q axes. As a result of this reluctance difference, angular momentum is produced between the d axis and the magnetic field B . It is isotropic in contrast to magnet (b). No angular torque is created because there is an equal amount of reluctance on the d and q axes .

This similar idea of reluctance variation will be used in SynRM to produce the torque. In an effort to line up with the magnetic field produced by the stator coils, the rotor will strive to do so. As the rotor will revolve because of the stator's revolving MMF, motion will be produced[27].

I.3. Differences between IM and synRM:

SynRM can be a more efficient alternative to induction motors in variable speed systems with low to medium power ratings, where , torque generation is based on the mutual flux's desire to choose the shortest path in the rotor iron circuit, which is typically referred to as the direct axis (d -axis) in electric machines with reluctance torque [29]. The efficiency difference, on the other hand, is greatest at high speeds with little torque , quicker dynamic response (as a result of smaller size in the same power range and a lower moment of inertia) and a wider speed range (due to the wide constant-power operation in comparison with IM)[30].

As well as higher efficiency in the same power range and frame size the SynRM operates always at the synchronous speed.

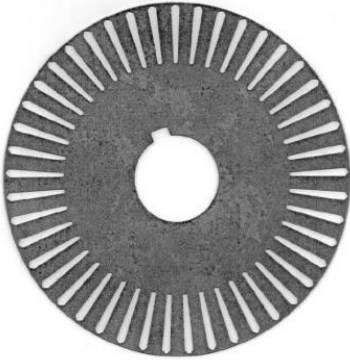
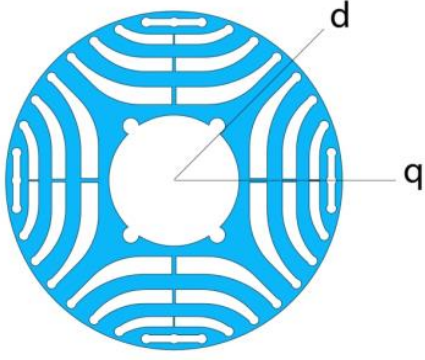
Type of Motor	IM	SynRM
Structure Sample of Rotor		
Advantages	<ul style="list-style-type: none"> _ direct connection to an AC power source _ low maintenance . _ low-cost . _ Simple and rugged design . 	<ul style="list-style-type: none"> _ highly efficient . _ high-speed . _ Greater torque. _ has a cold rotor.
Disadvantages	<ul style="list-style-type: none"> _ Low starting torque . _ High starting currents . _ Poor power factor . 	<ul style="list-style-type: none"> _ Difficulty controlling . _ Difficulty using sensors . _ high cost
Main Applications	induction motors are the most common motors used in industrial motion control systems, as well as in main powered home appliances .	Industrial applications,as well as in main powered home appliances .

Table I.1 A comparison of synRM and IM .

I.4. Diagnostic concepts and definitions :

Monitoring and diagnostics allow checking the status of machines in order to deal with the system's unpredictable faults during the operating phase. There are three types of terms used in fault diagnosis (monitoring, detection, and diagnosis).

I.4.1. Monitoring:

In industry, machine monitoring is tending to replace routine preventive maintenance. The objective is to equip these devices with a decision support system that informs the operator of the appearance of a fault before causing damage, and then to diagnose them by locating the faulty elements and identifying the root causes.

I.4.2. Detection:

The knowledge gained during the first stage allows you to have information on the system's behavior in the event of a failure, the most likely failures, the most critical failures, and the signs of their occurrence. To detect one or more system flaws, several successive direct or indirect measurements of magnitudes related to the system's operation must be taken. The detection stage determines whether or not a variation exists on the system. To do so, it is necessary to be able to classify observable situations as normal or abnormal.

I.4.3. Diagnosis:

Depending on the context and field of application, the term "diagnostic" can have a variety of meanings.

The goal of the diagnostic function in industrial processes is to identify possible causes and locate a failure or fault. This function is divided into two basic functions: localization, which determines the faulty functional subassembly, and identification, which determines the causes of an abnormal situation.

I.5. Different Types of faults:

In general, the electrical machine may operate in a variety of modes and may even be susceptible to a variety of unfavorable conditions, making it susceptible to various types of faults. Design, manufacturing tolerance, assembly, installation, working environment, load nature, and maintenance schedule can all lead to failure. A combination of one or more of the aforementioned causes is the most common cause of flaws. These machine flaws can be classified into three categories[31].

A) Electrical Faults:

An electrical fault is any type of fault with an electrical source. This category includes the following faults: unbalanced supply voltage or current ; overvoltage or overcurrent ; reverse phase sequence ; earth fault ; overload ; and short-circuit fault between turns or between phases.

B) Mechanical Faults:

The mechanical faults generally involve eccentricity and bearing faults . eccentricity, bearing faults , mass imbalance , stator/rotor friction , conductor displacement .

C) Environmental faults:

The machine's performance will be affected by both ambient temperature and external humidity. Machine vibrations are caused by installation flaws, foundation faults, and other factors.

Recently, a study has investigated different fault distributions of induction motors with rated power ranging from 0.75 kW to 150 kW, as well as probable scenarios and decision processes besides diagnosing those faults. The main distribution of induction motor faults, as shown in Fig.I.3, can be classified as rotor bar (7%) , stator winding (21%), bearing fault (69%), and shaft/coupling, among others (3%). Approximately two-thirds of the faults were caused by bearings, and one-fifth by stator windings[32]. A similar statistical survey on induction motor faults was conducted by IEEE and the electric power research institute (EPRI), and the percentage of different faults in relation to the total number of faults is reported in Table I.2[33].

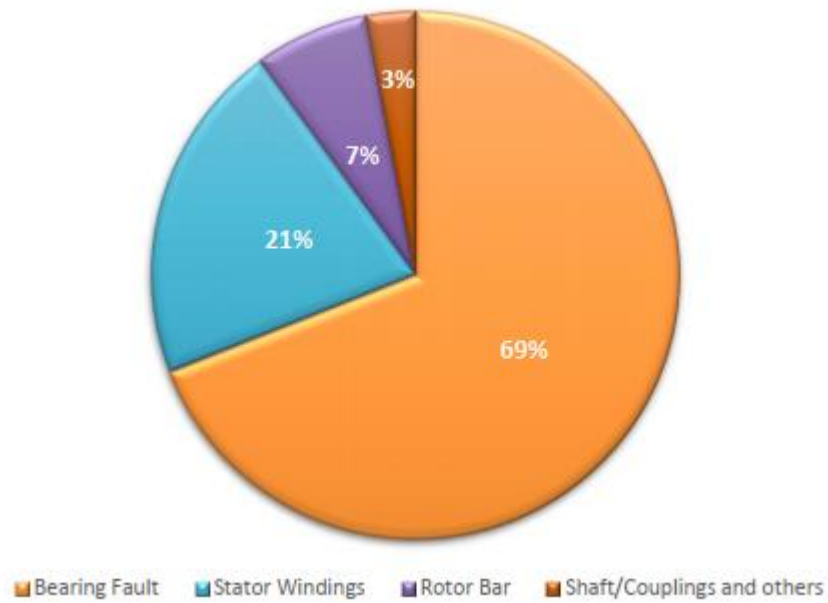


Fig. I.3. Different Fault distribution of an induction Motor[34]

Major fault components	Studied by	
	IEEE (%)	EPRI (%)
Rotor fault	8	9
Bearing fault	42	41
Stator fault	28	36
Others	22	14

Table I.2. Summary of Engine Malfunctions And Their Failure Rate

As mentioned before, the SynRM lacks windings in the rotor and the permanent magnets, so the faults could be divided as in figure I.4.

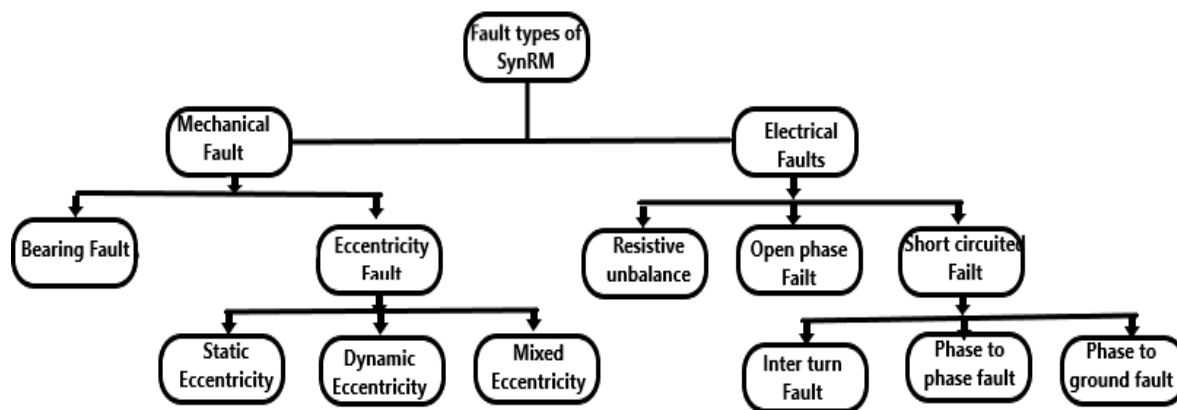


Fig. I.4. Fault Classification of SynRM.

I.5.1. Stator Winding related Faults:

Stator Winding related Faults According to an IEEE and Electric Power Research Institute motor reliability study [7], stator faults are mostly responsible for 37% of the failures in an induction motor, where many works have indicated that the majority of induction motor stator winding failures result from the destruction of the turn insulation. While Short-circuit faults form 21% of the stator faults occurring in electrical machines[32]. It has been reported that most short circuit faults begin as inter-turn faults [35]. The main cause of these is insulation material breakdown, occurring as a result of a combination of stresses (thermal, electrical, mechanical, and environmental) acting on windings during their operating life [36]. Insulation failures are attributed to different reasons, with the primary reason being excessive thermal stresses. Other reasons for insulation failure include voltage stresses, aging, vibrations, or mechanical handling during assembly, loose bracing for end windings, contamination caused by oil, moisture, etc., and also mechanical stress caused by overloading, high temperature, vibration, and the partial discharge of high-frequency inverter voltages[37]. So, in most cases, this failure starts as a turn-to-turn (inter-turn) fault which finally grows and reaches major ones such as coil-to-coil, phase-to-phase, or phase-to-ground failures, and ultimately causes motor breakdown[38][39]. They typically begin with a short circuit between turns before advancing to more critical problems. One of the primary causes of these problems is the deterioration of the insulating material that covers the conductors. This degradation is mainly due to abnormal heating in the winding. The current in the short-circuited turns reaches enormous values, and the resulting increase in temperature destroys all of the insulators, leading to the motor's ultimate failure[40] Figure I.5 represents the stator faults, while the Fig. I.6 depicts two examples of damage caused by a stator short circuit fault .

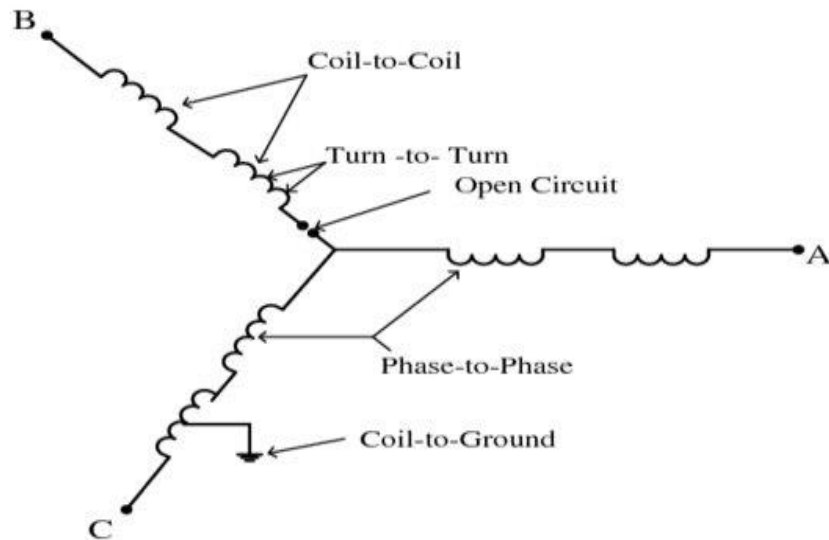


Fig. I.5. Graphical Representation of Stator Faults



Fig. I.6. Damage caused by a IM's stator short-circuit faults.

I.5.2. Stator Core related Faults:

Stator core problems are uncommon in comparison to stator winding problems, and they are usually not a major concern for small machines[41].

However, the repair/rebuild process is more expensive in the case of the primary stator Failed because the entire kernel must be replaced due to damage or problems With this in mind, there has been a lot of interest in researching and discovering the causes of basic problems and how to monitor the core in order to detect and prevent the basic failure of the stator to protect it The stator cores of the induction machine are made of thin, insulated steel sheets to reduce eddy current losses while increasing operational efficiency.

In the case of medium or large machines, the core is pressed after the base laminations are stacked to prevent individual lamination sheets from vibrating and increase the thermal conductivity in the core However, the most common reasons for stator cores resulting in process failure are heating of the core end zone caused by axial flow in the end winding region, core melting caused by

ground fault currents, lamination vibration caused by core clamping relaxation, and core tension loosening in the end winding. The end core is due to vibration during operation, manufacturing defects in the lamination, and the insulation between the plates.

However, the main causes of stator failure cores are due to core end-region heating resulting from an axial flux, in the end, winding region, Core melting caused by ground fault currents, lamination vibration resulting from core clamping relaxation, loosening of core tightening at the core end resulting from vibration during operation, manufacturing defects in laminations, interlaminar insulation failure, stator-rotor rubs during assembly and operation and arcing from winding failure. defects in laminations, and interlaminar insulation. However, the main causes of stator failure cores are due to core end-region heating resulting from an axial flux, in the end, winding region, Core melting caused by ground fault currents, lamination vibration resulting from core clamping relaxation, loosening of core tightening at the core end resulting from vibration during operation, manufacturing defects in laminations, interlaminar insulation failure, stator-rotor rubs during assembly and operation and arcing from winding failure.

I.5.3. Rotor related Faults:

The most common rotor faults in an induction machine may be classified as:

- 1 .Rotor winding related faults .
- 2 .Broken rotor bar fault.
- 3 .Bearing and gearbox faults.
- 4 .Eccentricity related faults.

However, since the SynRMs does not consisted of rotor winding or bars as conventional Induction machines, two kinds of faults would be represented in follows.

I.5.3.1. Eccentricity related Faults:

Machine eccentricity is explained as an unbalanced air gap between the stator and rotor[42]. Eccentricity is prevalent in rotating electrical devices; some manufacturers and users define a maximum allowable level of 5%, whilst in other circumstances, users allow for a maximum level of 10% of the air gap length [43]Manufacturers, on the other hand, usually attempt to keep the total eccentricity level as low as possible in order to avoid vibration, noise, and imbalanced magnetic pull[44]. Since an induction machine's air gap is significantly smaller than that of other types of machines of comparable size and performance, this type of machine is more sensitive to changes in the length of the air gap. Air gap eccentricity is classified into two types: static and dynamic. The position of the minimal radial air gap length is fixed in space in the case of static air gap eccentricity. However, in the case of dynamic eccentricity, the center of the rotor is not at the center of the rotation and the position of the minimum air gap rotates with the rotor. Unless caught early, the eccentricity grows large enough to generate strong imbalanced radial forces that can induce stator-to-rotor friction, resulting in a major machine breakdown [45].

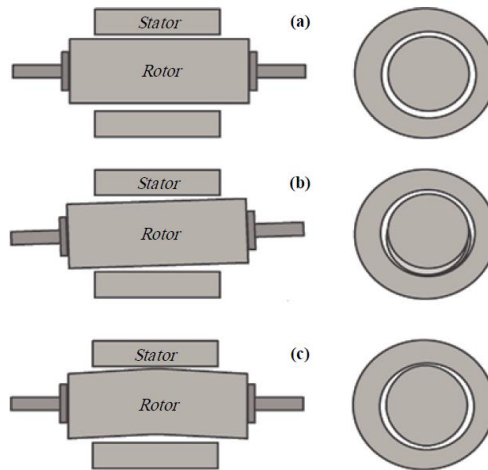


Fig. I.7. Types of eccentricity. (a) static, (b) dynamic, (c) mixed

I.5.3.2. Bearing and Gearbox Faults:

Bearing failures may account for 42 percent -50 percent of all motor failures, according to [46]EPRI (1982). Motor bearings may cost between 3% and 10% of the actual cost of the motor, but the hidden costs of downtime and lost production combine to make bearing failure an expensive abnormality[47]. Ball-bearing faults are classified as outer bearing race defects, inner bearing race defects, and ball defects. Different stresses acting on a bearing can cause excessive audible noise, uneven running, decreased working accuracy, mechanical vibrations, and increased wear. More than two decades ago, few bearing failures were electrically induced, but a study by [48]in the early 1990s revealed that bearing failures are approximately 12 times more common in converter-fed motors than in direct on-line motors. Mechanical issues, as discussed in [47],continue to be the leading cause of bearing failure. As reported in [46]EPRI (1982), bearing faults may account for 42%-50% of all motor failures, motor bearings may cost between 3%-10% of the actual cost of the motor, but the hidden costs involved in downtime and lost production combine to make bearing failure a rather expensive abnormality [47].Ball-bearing related defects can be categorized as outer bearing race defects, inner bearing race defects and ball defects. Different stresses acting upon a bearing may lead to excessive audible noise, uneven running, reduced working accuracy, and the development of mechanical vibrations and as a result, increased wear. More than twenty years ago, few bearing failures were electrically induced but at the beginning of the 90's a study by [48]showed that bearing failures are about 12 times as common in converter-fed motors as in direct on-line motors. However mechanical issues remain the major cause of bearing failure as discussed in[47].

I.6.diagnostic methods:

During the past fifteen years there has been a substantial amount of research into the creation of new diagnosis failures techniques for electrical machine drives[49], The accurate identification and processing of signals is necessary for error detection, In order to solve electrical issues, and have been developed fours diagnostic techniques[50].

I.6.1. Method based on signals:

Signal-based methods utilize measured signals rather than explicit input-output models for fault diagnosis. The faults in the process are reflected in the measure signals, whose features are extracted and a diagnostic decision is then made base on the symptom analysis and prior knowledge on the symptoms of the healthy systems, Therefore signal-based fault diagnosis methods can be thus classified into time-domain signal based approach, frequency-domain signal based approach and time-frequency signal based method[51].

I.6.2. Technique based on artificial intelligence :

This technique usually requires a neural network or a learning machine to reach a correct fault diagnosis Alternately, a defect detection requirement calls for the usage of a bidirectional long-term memory encoder, therefore memory can be seen as a drawback due to the pricey hardware needed[50].

I.6.3. Hardware-based techniques:

You can also find hardware-based methods in the literature that need external sensors, including fluxgate sensors, transverse magnetic sensors, or temperature sensors. The main issue with this strategy is that it makes the system more expensive and complex [13].

I.6.4. Model-based techniques:

For model-based methods to work, models of real-world systems or industrial processes must be accessible. These models can be found by using physical principles or systems identification techniques. Algorithms for defect diagnosis are created based on the model to keep track of how closely the models anticipated outputs match the measured outputs of real systems[51].

I.7. Conclusion:

This chapter represents theories relating to the SynRM (constitution, principle ...etc) and faults that could occur on this machine and their diagnostic methods, particularly the inter-turn short circuit fault. SynRMdifferent control techniques with a complete comparative study were also discussed.

Chapter II

Modeling of Inter-Turn Short
Circuit Faults for SynRM and
Their Detection Techniques

II.1. Introduction:

Many studies have been conducted to identify inter-turn short circuit faults in various electrical machines such as IM, PMSM, and so on; nevertheless, only a few ITSCF detection systems have been employed. These, in general, rely on noninvasive on-line monitoring and analysis of electrical and/or electromagnetic quantities, such as stator current, voltage, impedance, or flux. The reported techniques can however impose significant drawbacks in diagnostic capability and are particularly limited in effective recognition of early fault stages; for instance, minor changes in operating conditions, such as load variation, supply unbalance and inherent asymmetry, in particular at nonstationary conditions, can greatly affect their diagnostic performance [52][53]. Additional drawbacks are posed by the challenges of fault location and fault severity diagnosis [53]. Artificial Neural Network Time-Frequency Representation [54], statistical algorithms based on the Hidden Markov Model to classify electrical faults [55], and odd frequency harmonics in currents [56],[57] have all been proposed for the SynRM. These studies either lacked proper modelling or were confined to certain operational conditions. Nevertheless, such studies do not focus on detection in a closed-loop control system, where most open-loop failure detection approaches cannot be readily translated to a reliable closed-loop control system in which the fault signal is masked by external control signals thought to be noise, especially when they are of modest scale. As a result, the fault spreads throughout the system [42] and the detection mechanism cannot differentiate between normal noise and the incidence of the fault [58]. As a result, in this chapter, a new model of SynRM with inter-turn short circuit fault (ITSCF) called the faulty model will be presented in order to study the impact of ITSCF on SynRM, followed by descriptions of two well-known methods of detecting ITSCF, which are the Signal-based approach and Model-Based techniques, as well as fault analysis and method comparison that includes advantages and disadvantages [42].

II .2 Inter-turn short circuit fault on SynRMs:

Among the most important aspects of ITSCF in IM devices is its intrinsically robust evolution and self-intensifying behavior, which yields one of two outcomes.

The first is that in other failures, the fault-causing cause must persist and be amplified indefinitely in order to enhance fault severity. The fault will not be aggravated if the cause arising from the fault is eliminated; However, if the fault-generating component (for example, chemical agents that degrade insulation) is removed in the ITSCF, the fault intensity grows rapidly and leads to more defective turns.

The second point to be mentioned is that there is a model study in [59] that the ITSCF in a 15 kilowatt IM can develop a phase-to-ground fault in less than 5 s. Knowing that there are experimental studies of the realistic and practical error conditions in instant messages classified as 3.7, 2.2, and 11 kW, respectively, were reported in [60][61]. The three studies recorded different transition periods from onset Interface fault phase to phase-to-earth fault. So ITSCF will soon lead to more problems. If ITSCF is not caught early, it will grow and create phase-to-phase and phase-to-ground errors [62][63].

As a result, the destructive power of this error in machines is not the same. To determine the detrimental effect of ITSCF on SynRM, health models and SynRM with ITSCF are described, with comprehensive information and accurate mathematical models.

used as follows:

II .2.1 Healthy Model of the SynRM in the abc frame:

The three-phase voltage of the SynRM can be represented in the a,b,c axis stationary reference frame as follows which was used in[64]

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

Where v_a, v_b, v_c are the phase voltages, R_s is the stator winding resistance i_a, i_b, i_c are stator currents, where L_{aa}, L_{bb} and L_{cc} are the a,b and c phase self-inductances $L_{ab}, L_{ac}, L_{ba}, L_{ca}, L_{ba}$ and L_{cb} are the mutual inductances between the stator windings. Assuming that the stator windings are sinusoidally distributed windings, the self and mutual inductances of the SynRM can be expressed as:

$$\begin{aligned} L_{aa} &= L_{1s} + L_A + L_B \cos(2\theta_e) \\ L_{bb} &= L_{1s} + L_A + L_B \cos\left(2\theta_e + \frac{2}{3}\pi\right) \\ L_{cc} &= L_{1s} + L_A + L_B \cos\left(2\theta_e - \frac{2}{3}\pi\right) \\ L_{ab} &= L_{ba} = -\frac{1}{2}L_A + L_B \cos\left(2\theta_e - \frac{2}{3}\pi\right) \\ L_{bc} &= L_{cb} = -\frac{1}{2}L_A + L_B \cos(2\theta_e) \\ L_{ca} &= L_{ac} = -\frac{1}{2}L_A + L_B \cos\left(2\theta_e + \frac{2}{3}\pi\right) \end{aligned} \quad (2)$$

Where L_{1s} is the leakage inductance, L_A is the parameter which is unrelated to the rotor position, L_B is the parameter which is related to the rotor position and θ_e is the electrical rotor position of the motor. The SynRM's back EMF caused by mutual inductances and also saliency effect. The back EMFs of Synchronous Reluctance machines are called extended back EMF[65]. The electromagnetic torque is indicated as:

$$T_e = \frac{3}{2} p (L_d - L_q) i_d i_q \quad (3)$$

L_d and L_q are the direct and quadrature axes inductances respectively in the function of i_d and i_q currents as stated in[18][66]. Generally speaking, in order to enhance the control algorithm, the i_d may be defined as a constant current; the electromagnetic torque would then be reduced to

$$T_e = K i_d^* i_q^* \quad (4)$$

The motor dynamic equation is expressed as:

$$T_e = J \frac{d\omega_m}{dt} + B_m \omega_m + T_L + T_k \quad (5)$$

where T_L is the load torque, J the inertia moment of the system rotating parts, ω_m is the motor mechanical speed, B_m the viscous friction coefficient, T_k the constant friction load and p the number of pole pairs.

The electrical rotor speed and position are expressed as:

$$\omega_e = \frac{p}{2} \omega_m \quad (6)$$

$$\theta_e = \frac{p}{2} \theta_m$$

In order to simplify the equation, the electrical angle can be neglected in all previous inductances in (2) where the inductances will be as follows.

$$L_{aa} = L_{1s} + L_A + L_B \cos(2\theta_e) \quad (7)$$

$$L = L_{1s} + L_A + L_B$$

$$L_{aa} = L_{bb} = L_{cc} = L$$

The whole of the mutual becomes as:

$$M = -\frac{1}{2}L_A + L_B \quad (8)$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (9)$$

II .2.2 Faulty Model of the SynRM in the abc frame:

Several models have been developed to define an AC machine with short-circuit inter-turn faults[67][68], but this model takes into account the saliency effect. Fig.II.1 depicts a simplified diagram of the SynRM stator winding with a short circuit in phase A with n turns equal to short-circuited inter-turns and the total number of turns in each phase is identical and equals N , resulting in $\mu = n/N$. Where i is the current in the short circuit, and R_f is the resistance that models the insulation failure, its value depending on the fault severity. When R_f decreases toward zero, the fault evolves into a full inter-turn short circuit. This phenomenon causes asymmetry in the machine's armature current and degrades machine performance. Furthermore, it can cause gradual insulation breakdown in the entire stator windings, resulting in phase-to-phase short circuits and other problems.

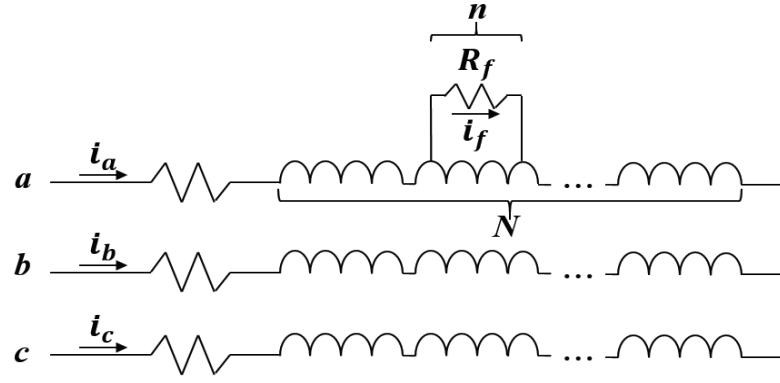


Fig. II.1. Equivalent circuit of a series connected SynRM with an inter turn short-circuit fault in the phase a.

The stator equations for SynRM with inter-turn fault subscription f in-phase a and described in the ABC reference frame are seen in (10) where all inductances should be simplified as a healthy model:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \\ v_f \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & -uR_s \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ uR_s & 0 & 0 & -uR_s - R_f \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix} + \begin{bmatrix} L & M & M & -uL \\ M & L & M & -uM \\ M & M & L & -uM \\ -uLuMuM & -u^2L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix} \quad (10)$$

III.2.3 SynRM Model with ITSCF in the dq0 frame:

The motor model will be in frame dq0 as in (11) after applying Park transformation to (10)

$$\begin{aligned} v_d &= R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q + \Delta v_{df} \\ v_q &= R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \Delta v_{qf} \end{aligned} \quad (11)$$

$$\Delta v_{df} = -\frac{2}{3} v R_s i_f \cos \theta - \frac{2}{3} v L_d \cos \theta \frac{di_f}{dt} + \frac{2}{3} v \omega e^i f (L_d - L_q) \sin \theta$$

$$\Delta v_{qf} = \frac{2}{3} v R_s i_f \sin \theta + \frac{2}{3} v L_q \sin \theta \frac{di_f}{dt} + \frac{2}{3} v \omega e^i f (L_d \sin \theta - L_q \cos \theta)$$

The inductances of the dq will be as (12), like [69] and by the transformation of the park.

$$\begin{aligned} L_{dq} &= p L_s p^{-1} = \text{diag} \{L_d L_q L_{1s}\} \\ L_d &= L_{1s} + \frac{3}{2} (L_A + L_B) \\ L_q &= L_{1s} + \frac{3}{2} (L_A - L_B) \end{aligned} \quad (12)$$

II.3 Detection Fault Methods:

There are many methods for detecting faults that have been reached by researchers, but for an accurate treatment of faults in motors, the most efficient methods must be addressed in determining the faults accurately, and as previously mentioned, there are four methods that are the most common effect, and we will mention them in this chapter the most efficient method is signal-based Approaches

II.3.1 Signal Based Approaches:

Signal-based methods utilize measured signals rather than explicit input-output models for fault diagnosis during operation. Many harmonics may be present in motor current signals where the faults in the process are reflected in the measured signals, where frequency spectrum shows many peaks whose features are extracted and a diagnostic decision is then made based on the symptom analysis and prior knowledge on the symptoms of the healthy systems [51]. This is known as the motor current signatures, which are different between faulty and healthy motors, because different electrical and mechanical faults generate different signatures [53]. Signal based fault diagnosis methods have a widely application in real-time monitoring and diagnosis for induction motors, power converters and mechanical components in a system.

II.3.1.1 Fast Fourier Transform (FFT):

The method is based on the examination of the stator current and because it is easily accessible, and given its ability to detect both electromagnetic and mechanical faults, the analysis of the stator current occupies a privileged place in the diagnosis by analysis of the signals. This technique is known by the abbreviation MCSA (Motor Current Signature Analysis).

The MCSA was the subject of several research works, it consists in assigning to each defect a spectral signature characterizing it. In the same context, it has been shown that the severity of the defect is a function of the amplitude of the frequency components it generates, and in particular of the lines already present in the healthy motor (space harmonics) [70].

The faults of the asynchronous machine are reflected in the spectrum of the stator current by:

- 1-The appearance of spectral lines whose frequencies are directly linked to the rotational frequency of the machine, to the physical parameters of the machine (number of rotor bars and number of pairs of poles).
- 2 -The modification of the amplitude of the spectral lines, already present in the spectrum of the current. Monitoring via the stator current requires a good knowledge of the faults and their signatures. They are currently used in the context of grid-powered machines and for finding characteristic fault frequencies [71].
- 3 -We distinguish a large number of works based on stator current analysis, as well as this analysis is applied in different faults. The signatures of the stator currents are used for the detection of bar breaks, we also distinguish for the detection of eccentricity faults [70].

The measurement points of the different signals (current, flux, vibrations,..) using a variety of devices are illustrated in the figure II.2.

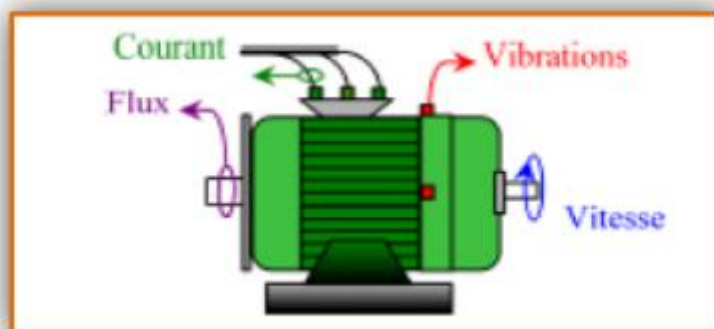


Figure II.2. The different measurement points.

The analysis of a signal is therefore a source of information. Indeed, the measurement of a signal indicates oscillations which can be harmonic, stochastic in nature or both simultaneously. The variation of these signals can be related to faults. To extract the characteristics of a signal relating to a defect, generally, the amplitude or the amplitude densities are extracted. However, there are other possibilities which consist in determining the autocorrelation functions, the Fourier transforms or the spectral density [72].

In 1807, the Fourier transform came into existence, Fourier analysis is a major basis of physics and mathematics. It is inseparable from signal processing, for two main reasons. The first is the universality of the concept of frequency on which it is based. The second is due to the very structure of Fourier analysis which easily lends itself to common transformations such as linear filtering by translating them in a particularly simple way.

The principle of the Fourier transform is based on the fact that any periodic function can be represented as the sum of a series of sines and cosines whose amplitudes are varied on the one hand by multiplying them by coefficients, and on the other hand the phases by shifting them so that they add up or compensate each other [73].

$$x(f) = \int_{-\infty}^{+\infty} x(t) \cdot e^{-j2\pi \cdot f \cdot t} dt \quad (13)$$

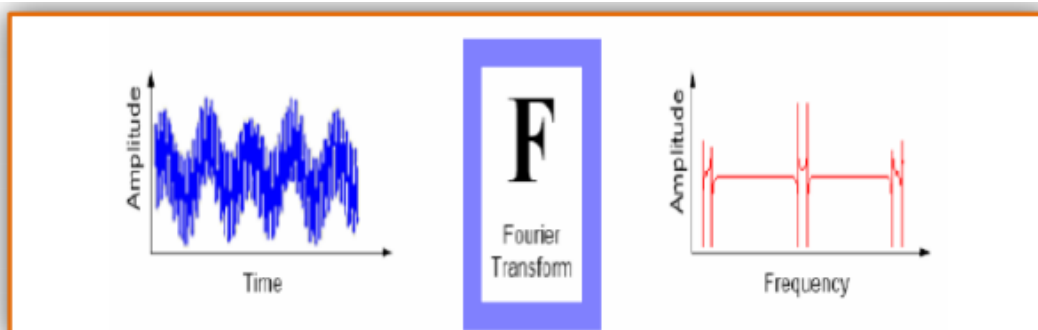


Figure II.3. The principle of the Fourier transform .

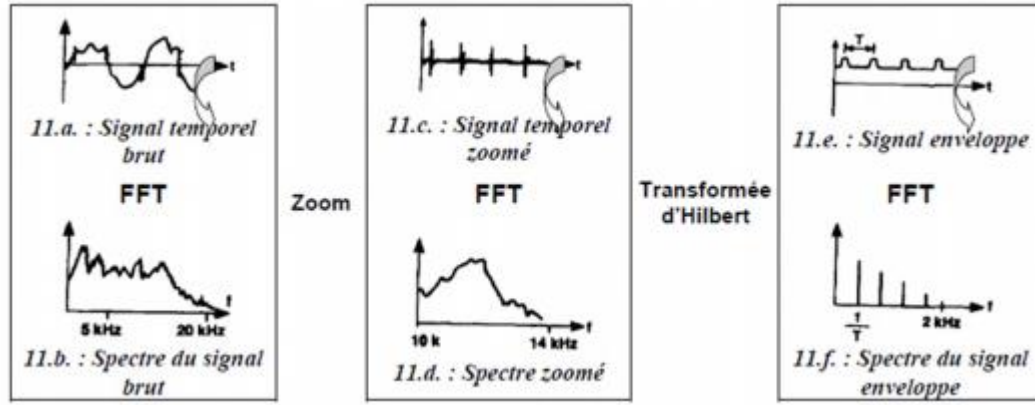


Figure II.4. envelope calculation principle [74]

The fast Fourier transform is a mathematical technique for fast computation developed in 1965 by J. W. Cooley and J. W. Tuckey. The FFT makes it possible to reduce the calculation of the discrete Fourier transform from N^2 to $N \cdot \log(N)$ operations. This reduction in computational complexity was enough to make many problems related to spectral analysis easily solvable. For a better visualization of a frequency analysis, the FFT is used through a sliding observation window [75]. Despite the introduction and success of the fast Fourier transform (FFT), it is therefore by definition not very suitable for the study of non-stationary signals. However, these signals are found much more often than stationary signals [70].

A computer can only process digital signals, these are obtained after sampling. In our case, the signals to be analyzed are the stator currents acquired or sampled using a dSpace 1104 card using Hall effect current sensors. The acquisition was made according to the following parameters:

- Sampling frequency: $F_e = 200000$ Hz ;
- Acquisition time: $T_a = 0.05$ sec
- The number of samples: $N_e = T_a \div T_e = F_e \cdot T_a = 200000 \times 0.05 = 10000$ Samples;
- Frequency resolution : $\Delta f = F_e / N_e = 200000 \div 10000 = 20$ Hz ;

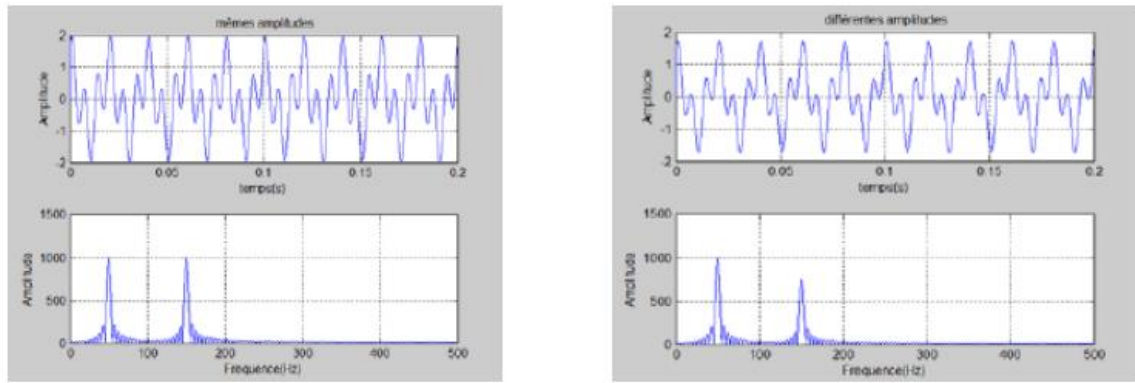
With a computer, it is impossible to calculate the FFT $X(f)$ for any value of the frequency f . Therefore, the FFT is only calculated for multiples of Δf .

This is the notion of the Discrete Fourier Transform (DFT). Consequently, the DFT $X(n)$ of a sampled signal $X(k)$ is given by:

$$X(n) = \sum_{k=1}^{N_e} x(k) e^{-j2\pi k \frac{n}{N_e}} \quad (14)$$

with $n=1, 2, \dots, N_e$

The first example on a stationary signal is composed of a sum of two sinusoids of frequencies (50 and 150 Hertz) of the same amplitude, of which FFT see figure (II.5.a), and of different amplitude, of which FFT see figure (II.5.b). It can be seen that with Fourier analysis, the two signals are identical in spectral lines and of course the amplitudes differ.

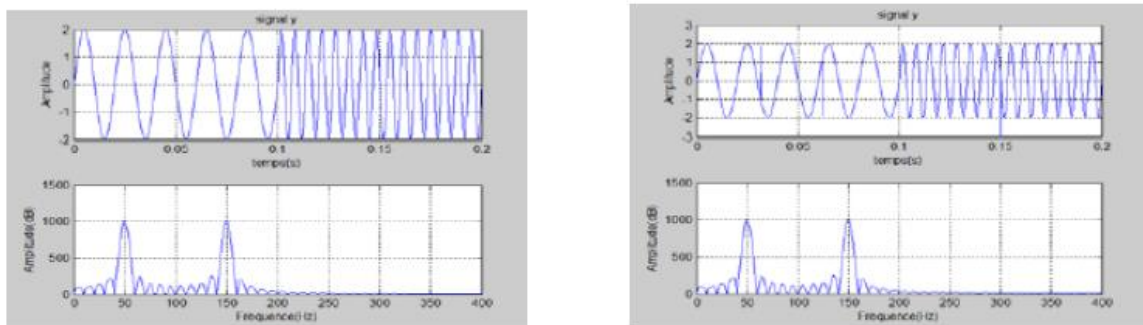


(a) : same amplitudes .

(b) : different amplitudes .

Figure II.5. Time and frequency representation sum of two sinusoids .

The second example on a non-stationary signal, the frequency shape changes over time, going from a sinusoid of 50Hz to another of 150Hz with the same amplitude. We note that the frequency analysis is unable to give information on the temporal localization of the change of regime in the signal of the figure (II.6). It can also be seen that in figure (II.6.b) a pulse is added compared to figure (II.6.a), but without any impact on the FFT [75].



(a) : succession of two sinusoids.

(b) : succession of two sinusoids +pulses

Figure II.6. Loss of temporal location.

II.3.1.1.1 Power active and reactive:

One of the methods used to detect the Different faults of the stator is based on analyzing the active power and reactive power harmonic after applying Fast Fourier Transform , It has been used in many researches , As a failure indication, the second harmonics of the instantaneous active or reactive powers are used .This technique was also used in [76]where was assess comprehensive experimental test in gunder both healthy and fault situations on a 35kW machine drive prototype were used to develop a trip redundant 9-phase (3x3-phase) permanent magnet aided synchronous reluctance machine (PMA SynRM) drive. When the system is functioning properly, the second harmonic of the active and reactive powers in each of the three 3-phase sets is comparable and very near to zero. Or if a turn fault is detected the mitigation action TSC will be applied to the fault set if the 2nd harmonic in one three-phase set is sign if icantly greater than the reference value in the healthy condition and that of the otherwhere-phase sets .It was also discussed in[77]where it was comparing the active power flowing in and out of the machine with the blocked and rotating rotor in

six-phase synchronous reluctance machine to determine the machine efficiency And the detection of a Inter-Turn Short-Circuit Faults if any. As in [78]the reactive power was used in some algorithms to adjust voltage and speed control and increase efficiency of domestic and industrial fan/pump.

The Power active and reactive is re presented in the following two equations :

$$P = \frac{3}{2} (v_d * i_d + v_q * i_q) \quad (15)$$

$$Q = \frac{3}{2} (v_q * i_d + v_d * i_q)$$

Where :

P : active power .

Q : reactive power .

V_d : the phase voltage in d axis.

V_q : the phase voltage in q axis.

I_d : the stator current in d axis .

I_q : the stator current in q axis.

However, the most harmonic component that is often extracted for locating the inter-turn short circuit defect is the second harmonic, which is the most harmonic component.

II.3.1.1.2 Stator Currents:

It is one of the ways detects Faults that are classified within Signal Based Approaches techniques Where this method is based on analyzing the current curves of the stator iaibic by applying Fast Fourier Transform (FFT) , decomposes a time domain into components of different frequencies, which will then enable us to discover the inter-turn short circuit , Were call that in the event of the inter-turn short circuit, the frequency changes and we have a frequency fit_{sc} represented by the following expression:

$$f_{itsc} = f_s \left(1 \pm k \frac{z}{p} \right) \quad (16)$$

f_s = frequency of the power supply.

K = positive integer.

z =the number of stator slots.

p= the number of pole pairs.

where the fundamental frequency amplitudes of the three-phase current are denoted by ia, ib, and ic. Mechanical issues will result in specific current tharmonics in the stator current and distortions in the flux distribution inside the motor[50].

II.3.1.1.3 Park Vector Approach:

This method is considered as a one of the most used methods by researchers due to the high efficiency provided by its results, as all researchers seek the most accurate methods, especially in examining motors and detecting their faults, so identifying faults early is one of the most important

factors that attract researchers, in order to avoid many potential losses. this method depends mainly on the Park transformation, where the parameter is converted from a three-phase (i_a , i_b , i_c) to a two-phase parameter(i_d , i_q), then the work is on Park currents.

After the Park transformation and Under healthy condition, the current park components can be described as :

$$I_d = \frac{\sqrt{6}}{2} I \sin(\omega t) \quad (17)$$

$$I_q = \frac{\sqrt{6}}{2} I \sin(\omega t - \frac{\pi}{2})$$

Current monitoring using Park's approach is based on the fact that a Y-connected induction motor lacks homopolar or zero sequence current components as a result of the absence of a neutral wire. Nevertheless, the Parks vector technique has the benefit of eliminating the fundamental frequency of the current being monitored and boosting the amplitude of the components associated to faults[50].

In[79]the work was done in this way, and the results of experiments in it presents a non-invasive method for identifying failing winding insulation in three-phase transformers. The online diagnosis is based on recognizing the appearance of an elliptic pattern that corresponds to the transformer supply current Park's vector representation, whose major axis orientation is connected to the defective phase and whose ellipticity rises with the severity of the fault , and It has also been touched upon in study transformer behavior under the influence of inrush currents and/or incipient winding faults where Extended Park's Vector Approach (EPVA) based strategy provides reliable protection , enhanced sensitivity for internal faults and a truly three-phase detection factor for blocking trips on inrush transients[80].

The modulus of Park's vector $|i_s|$ is:

$$i_s = \sqrt{i_d^2 + i_q^2} \quad (18)$$

And it remains stable as long as the operation is in a healthy state, but if the stability of park vector is broken, then this represents the presence of faults.

II.3.1.2 Wavelet Transform:

Wavelets are mathematical functions that represent scaled and translated copies of a finite length waveform called the mother wavelet.

A wavelet transform is based on wavelets it is used to analyze a signal into different frequency components at different resolution scaler this allows revealing image is spatial and frequency attributes simultaneously f[81].

$$f(x) = \sum_{n=0}^{\infty} a_n f_n(x) \quad (19)$$

II.3.1.2.1 Time-scale analysis:

Time-frequency analysis studies the variation of frequency characteristics over time. But we can also consider the time-frequency representation as being a projection of the signal on fixed basis functions. Other approaches for the analysis of non-stationary signals consider that the non-stationary signals are superpositions of the calculated components of the basis functions which are more or less localized in time.

Continuous wavelets are better suited for time-frequency analysis and for visualization, while discrete wavelets are very useful in decomposition, compression and for the extraction of indicators[82].

II.3.1.2.2 The Continuous Wavelet Transform (CWT):

CWT consists in decomposing a signal into elementary components localized both in time and in frequency. This is done by translation (Fig.II.7) and dilation (Fig.II.8) of an analyzing wavelet called a mother wavelet. The coefficients of the CWT of a signal $x(t)$ at time b and a dilation a is given by the following formula (Fig.II.9) [83].

$$X_{CWT} = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) \psi * \left(\frac{t-b}{a} \right) dt \quad (20)$$

Where 'b' is a translation parameter and 'a' is a scale parameter that measures the expansion or contraction of the wavelet, $\psi(t)$ is the mother wavelet, the star indicates the conjugate of the function. Each value of the CWT wavelet transform is normalized by a factor $1/\sqrt{a}$.

The synthesis of $x(t)$ from the wavelet coefficients is described by the formula:

$$x(t) = \frac{1}{c\psi} \int_{-\infty}^{+\infty} X_{CWT}(a, b) \psi_{a,b} \frac{da db}{a^2} \quad (21)$$

With c is a constant given by the admissibility condition. Figure II.9 shows the CWT of the signal $x(t)$ (equation II.21) this figure shows two frequencies (100Hz and 10Hz) at two different scales, three pulses, two of which correspond to the signal pulses and third, at time 1s corresponds to the abrupt change of the two frequencies which shows discontinuity.

The wavelet transform consists of two main parts: the CWT and of the orthogonal wavelets and wavelet packets (the discrete wavelet transform).

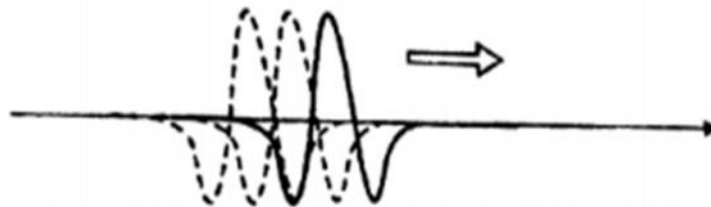


Figure II.7. Translation (change of position) of wavelets[84]

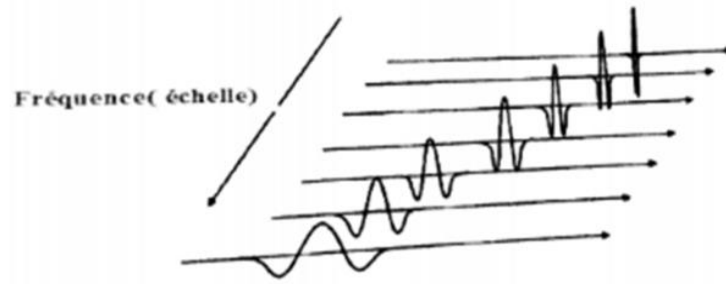


Figure II.8. Change of scale (level) of wavelets[83]

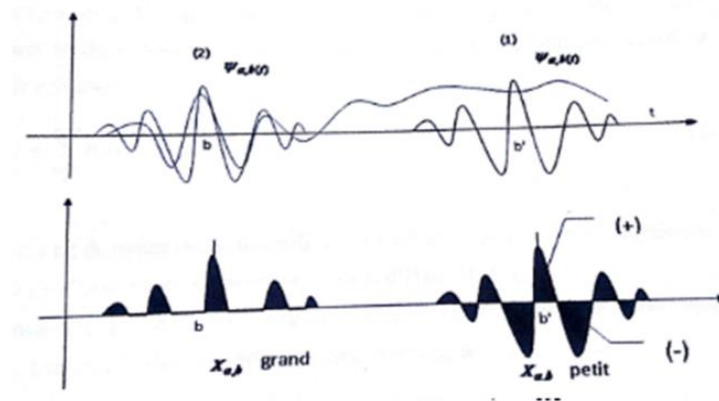


Figure II.9. Principle of the WT continue[83]

II.3.1.2.3 The discrete wavelet transform:

From the functional point of view, it is a question of replacing a continuous representation (a, b) with a discrete representation[83]. This is done by sampling the coefficients of the wavelet on hyperbolic which allows to have a non-redundant representation and digitizes the wavelet processing.

II.3.1.2.4 Wavelet packets:

As for the discrete orthogonal wavelet transforms, the packet wavelets require the use of orthogonal wavelets[83]. The principle of decomposition into wavelet packets is to remove the decomposition process from a signal in approximation and detail no longer only on the coefficients of approximation.

II .4. Comparison of Different Methods:

Table II.1. Comparison of different detection techniques for ITSCF

Approach		Powers	ModelBased	Park vector	Statorcurrents
Index					
1)	Additional Sensors	✓	×	×	×
2)	Parameter dependency	×	✓	×	×
3)	Detect the faulty phase	×	✓	×	✓
4)	Fault Severity	✓	×	✓	✓
5)	distinguish different faults	✓	×	✓	✓
6)	Immunity to the effects of operating speed	×	×	✓	✓
7)	Immunity to the effects of load level	×	✓	✓	×

The following table represents a comparison of the pros and cons of each technique where the mark ✓ shows the positives, while the mark ✗ shows the negatives .

In 1, we have 3 techniques that do not require the presence of more sensors, and one method that requires an increase in sensors, which is the technique of powers .

In 2, we find that the Model based technique is related to the model variables, unlike the rest of the techniques , as they are related to current or tension only.

In 3, we notice that we can determine the faulty phase in the model based and stator currents techniques , while we cannot determine that in Powers and Park vector techniques.

In 4, we found three techniques associated with severity of faults, in contrast to the model-based technique in which nothing appears.

In 5, the model-based method is the least type of errors to show unlike other methods which enable you to show many errors.

In 6, we can detect the fault in the Stator currents and Park vector techniques With changes in speed, while we cannot determine this in the Model based and Power techniques.

In 7, we can detect the fault in the current Model based and Park vector techniques with changes in load , while we cannot determine this in the stator current and Power techniques.

II .5. Conclusion

In this content we have examined the effect of ITSCF on SynRM we offer the theories regarding the most common detection methods, and compare which method has advantages and disadvantages. Furthermore, we decided three approaches based on constant currents, Park vectors, active and reactive forces approaches.

Chapter III

Validation of Three Detection
Techniques: Stator Currents ,
Extended Park Vector and
Active and Reactive Power

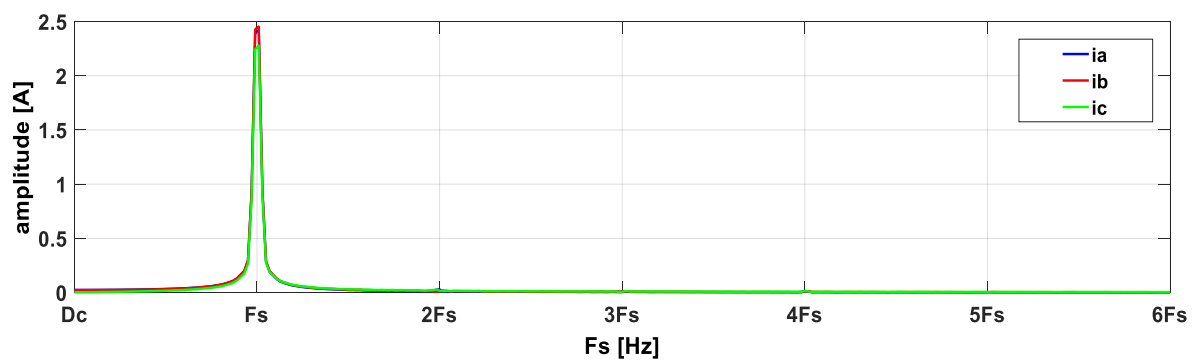
III.1. Introduction:

In a closed-loop control system, model-based approaches are often used to define ITSCF, so ITSCF signatures were evaluated using fast Fourier transform (FFT). The main objective is to identify the symptoms of ITSCF in each of the following techniques. Park vector approach, stator currents, active and reactive power numbers with different fault intensities applied to SynRM via a closed-loop control system.

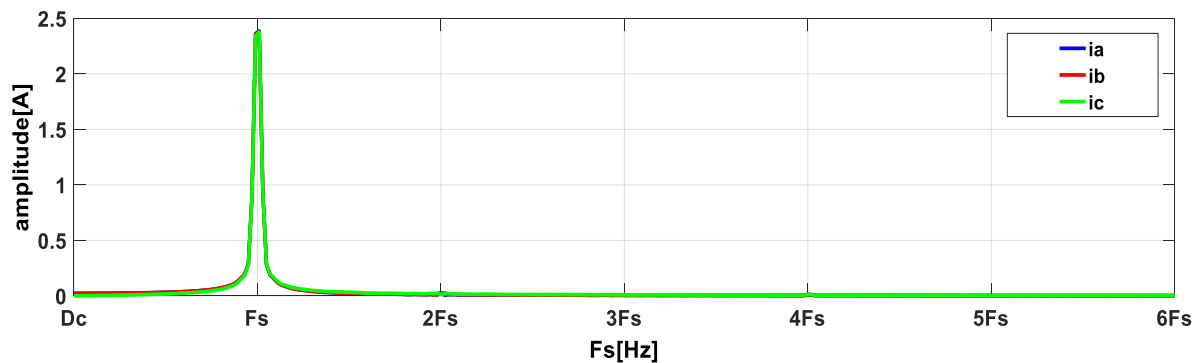
III.2. Stator Current Method :

$R=8\Omega$:

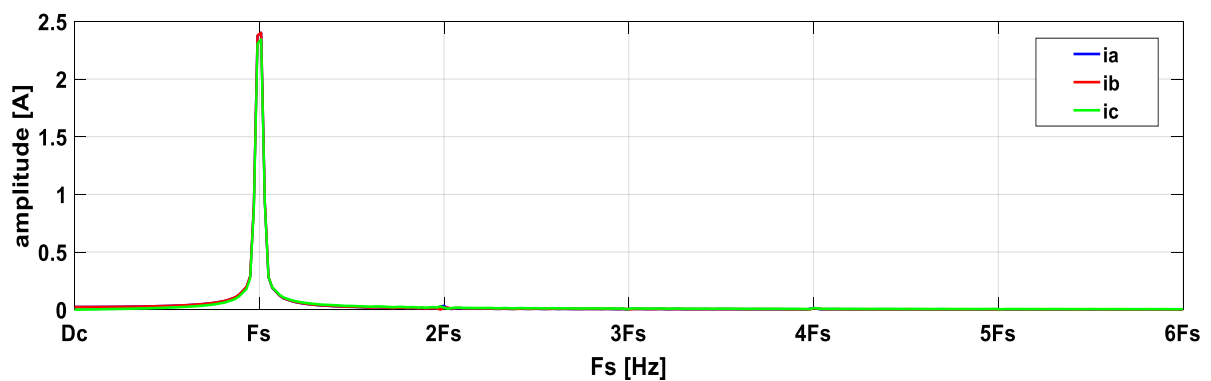
Healthy

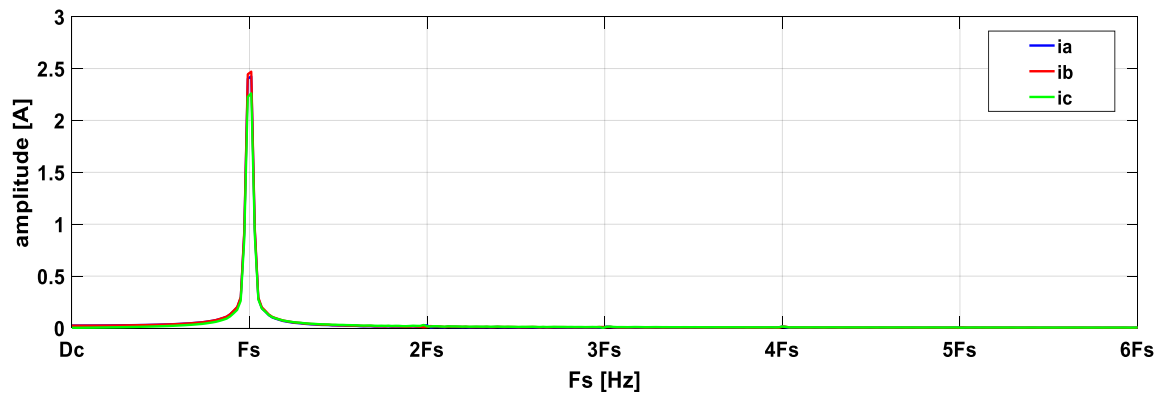
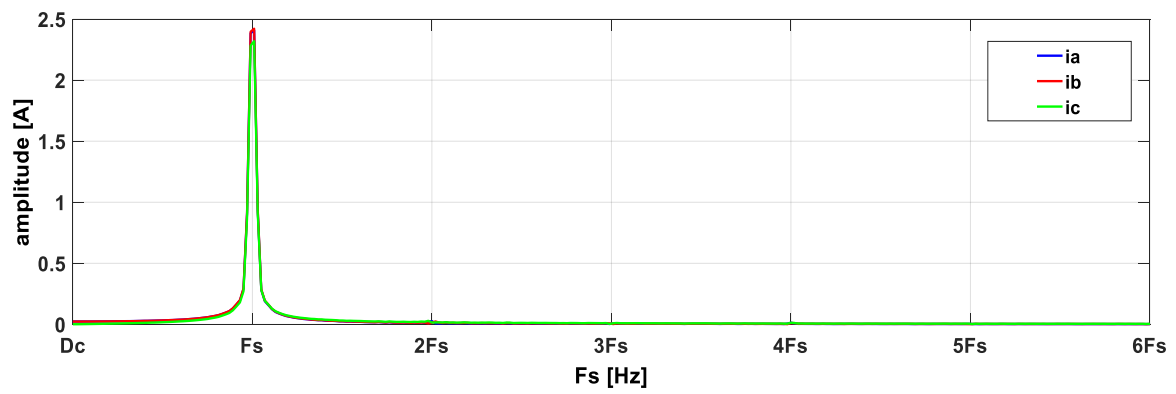
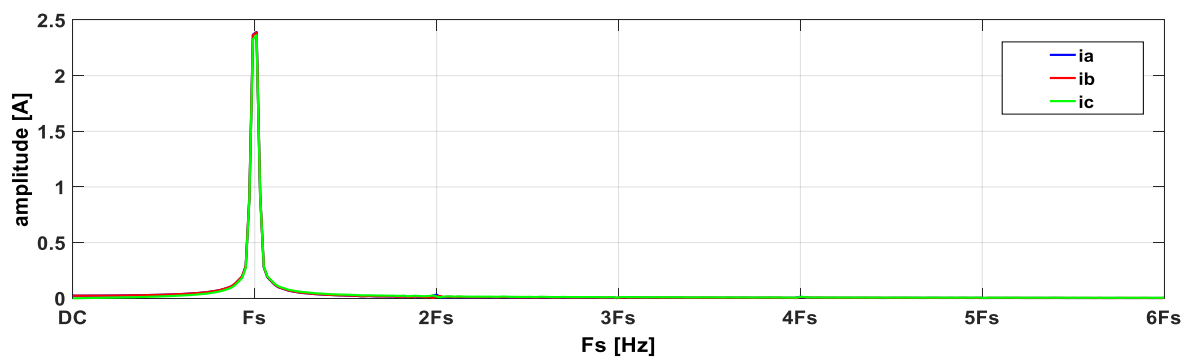


08 turns

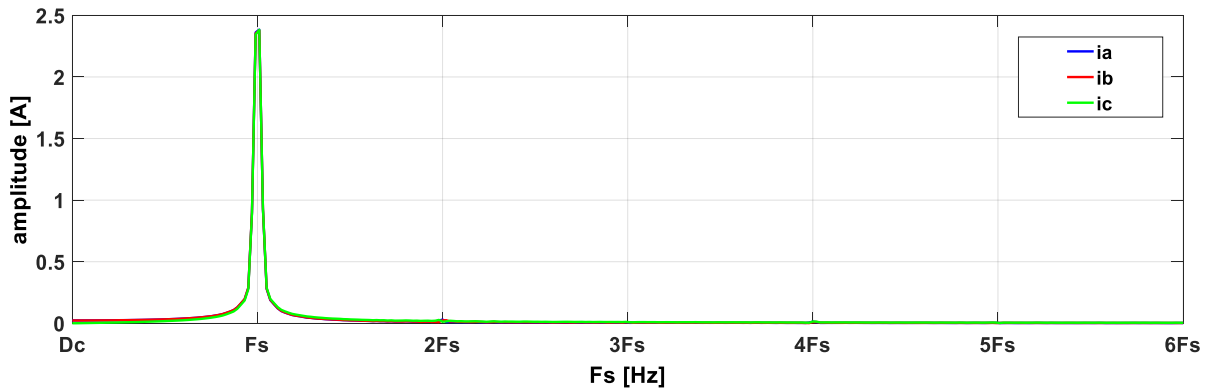


18 turns



32 turns**Figures III.1.** Spectrum of the stator current for different ITSCF , with $R_f = 8 \Omega$.**R=4Ω:****08 turns****18 turns**

32 turns



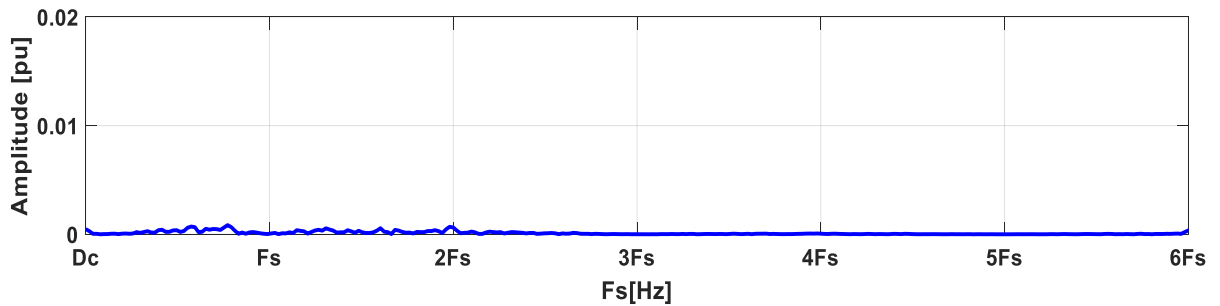
Figures III.2. Spectrum of the stator current for different ITSCF , with $R_f = 4 \Omega$.

By analyzing the behavior of the frequency components in Figures (III.1, III.2) the first harmonic is the component that can be based on it, as the figure shows that the first harmonic is strongly affected by the variable short circuit cycles, and the error index increases with the decrease in resistance ($R_f = 4 \Omega$, $R_f = 8 \Omega$). On the other hand, closed-loop control obviously affects stator currents.

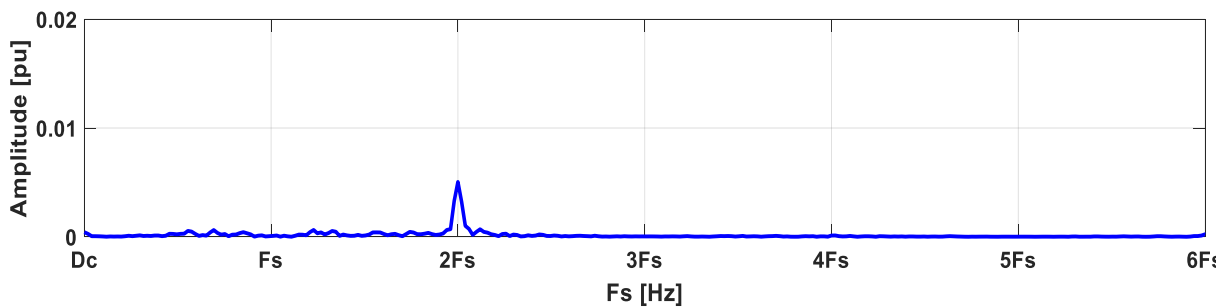
III.3. Extended Park Method:

R=8Ω:

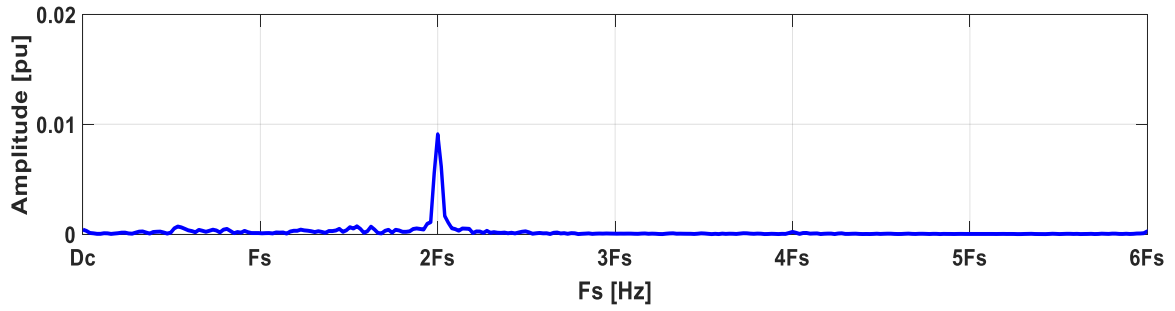
Healthy



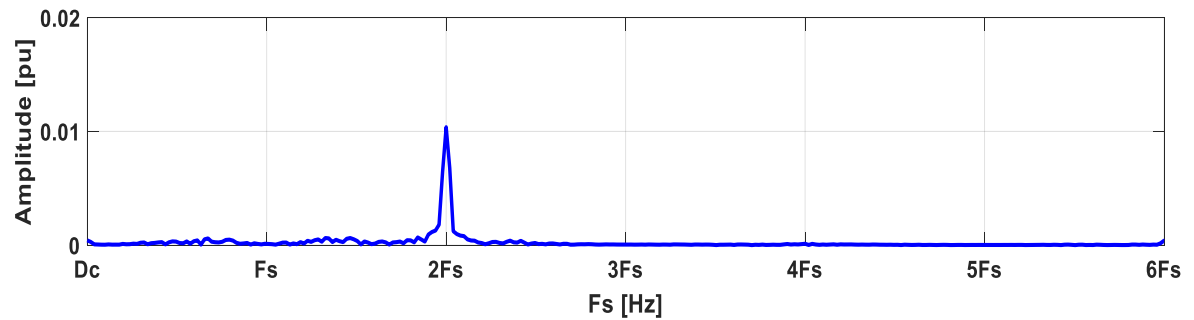
08 turns



18 turns



32 turns

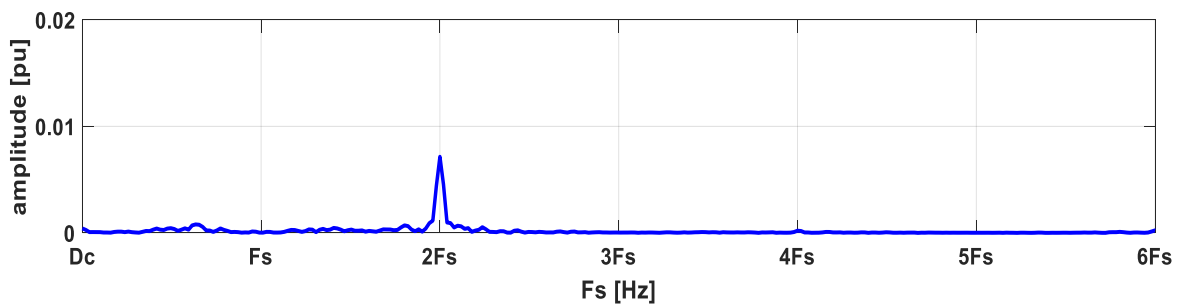


Figures III.3. Spectrum of the Extended Park for different ITSCF , with $R_f = 8 \Omega$.

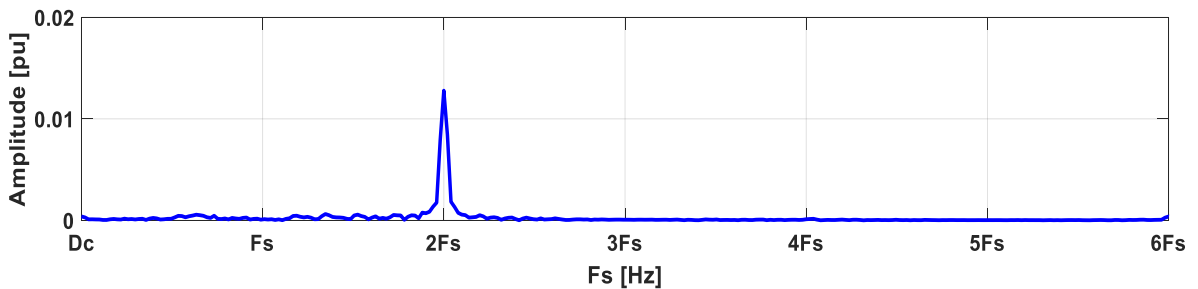
By observing the behavior of the frequency components at $R_f = 8 \Omega$ in the figure Figures III.3 we find that the second harmonic is reliable as it is strongly affected by the variable short circuit cycles.

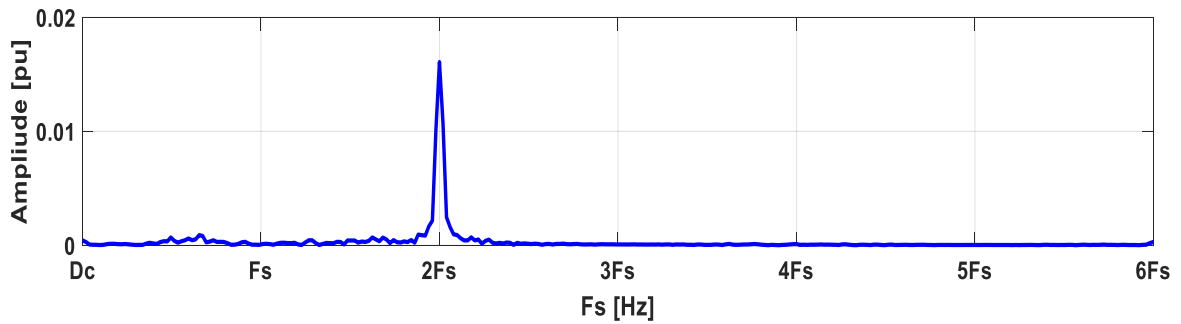
R=4Ω:

08 turns



18 turns



32 turns

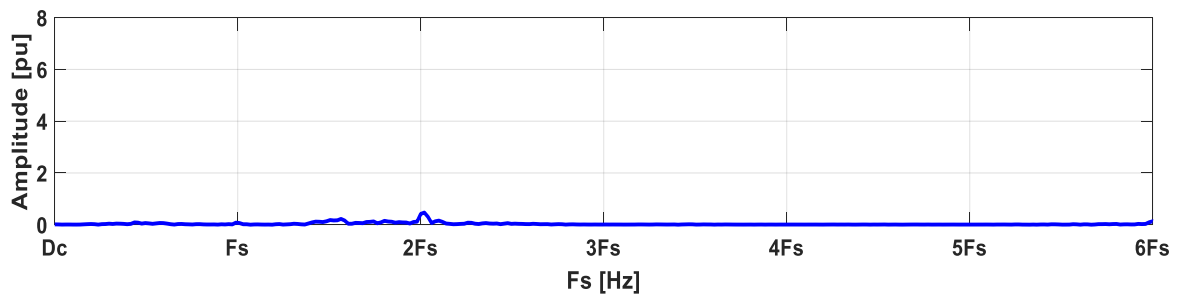
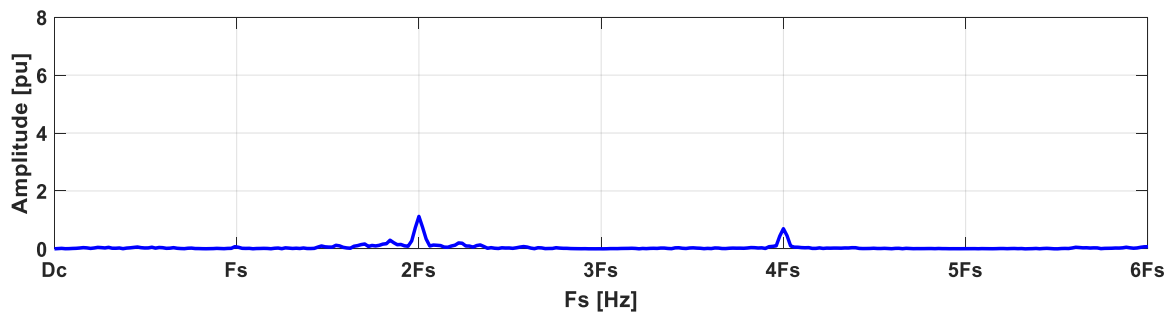
Figures III.4. Spectrum of the Extended Park for different ITSCF , with $R_f = 4 \Omega$.

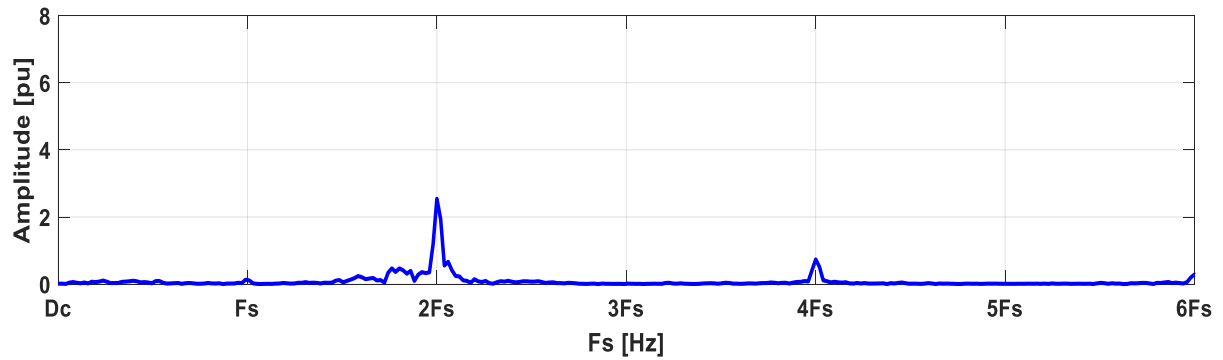
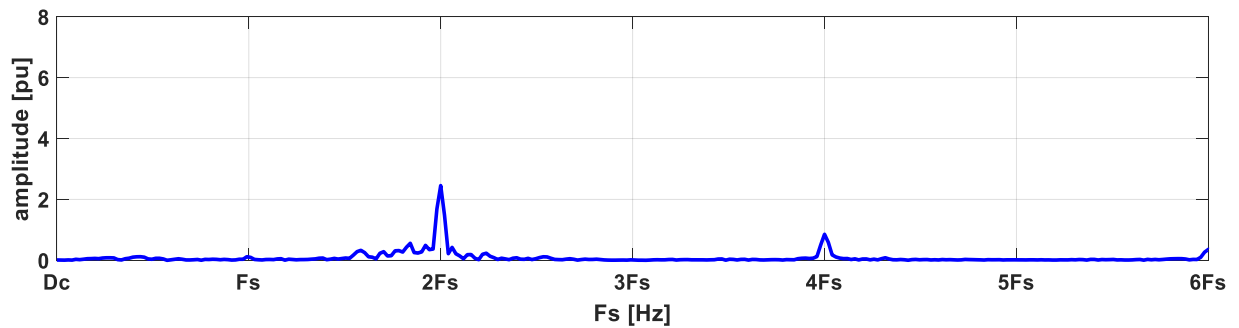
The figure shows Figures III.4 and at $R_f = 4 \Omega$ that changing the turns has a significant effect on the second harmonic , Furthermore, the park vector demonstrates that this approach outperforms the constant currents approach.

III.4. Active & Reactive Power Method:

III.4.1. Active Power:

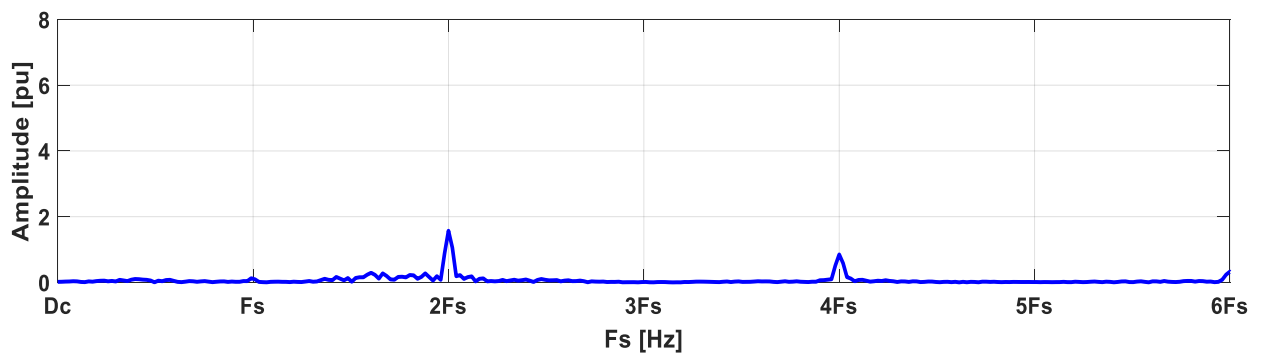
R=8Ω

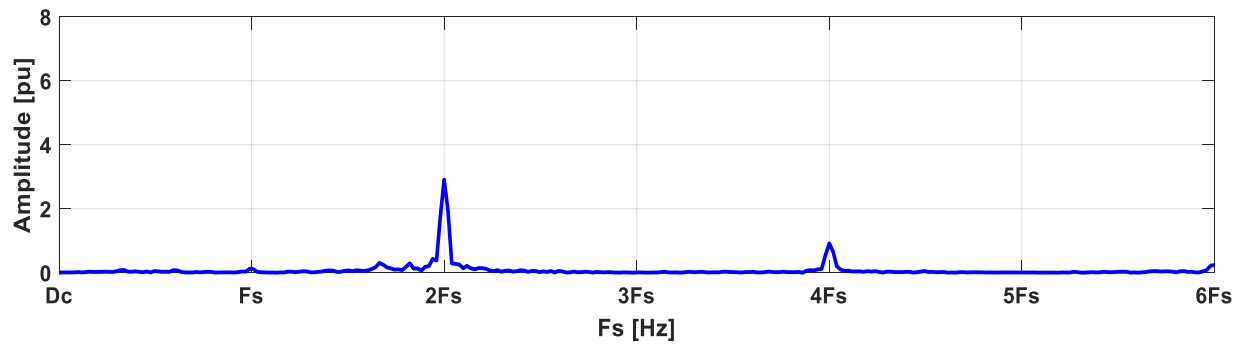
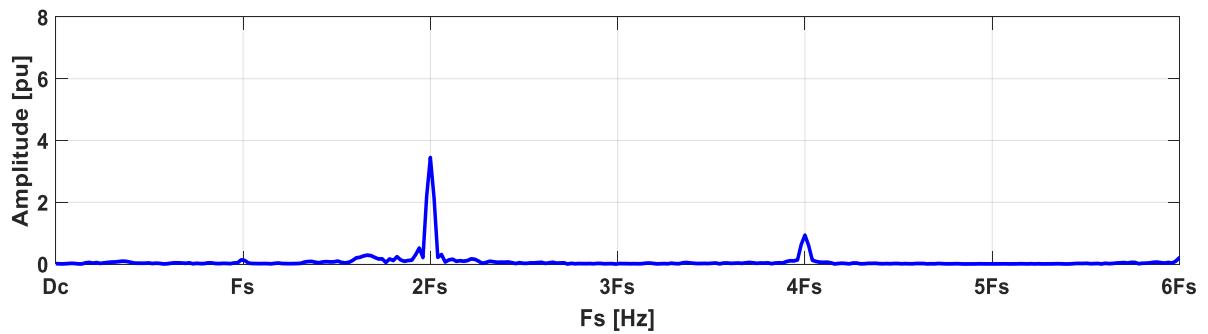
Healthy**08 turns**

18 turns**32 turns**

Figures. III .5. Spectrum of theActive Power for different ITSCF, with $R_f = 8 \Omega$.

R=4Ω

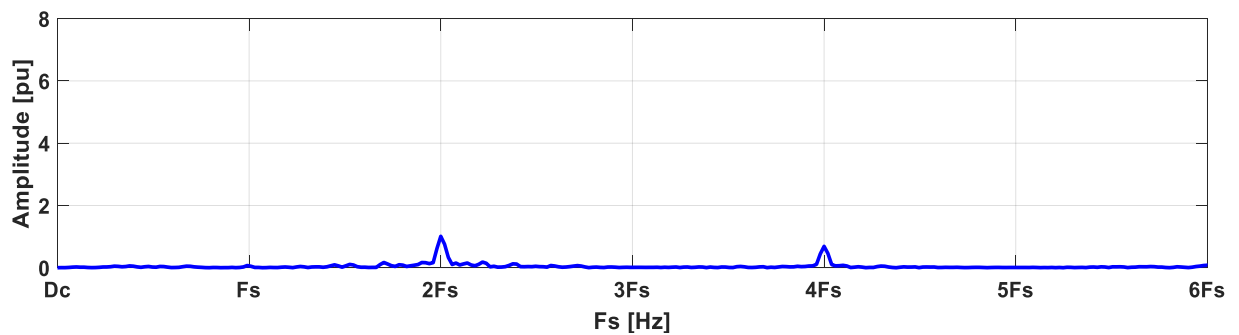
08 turns

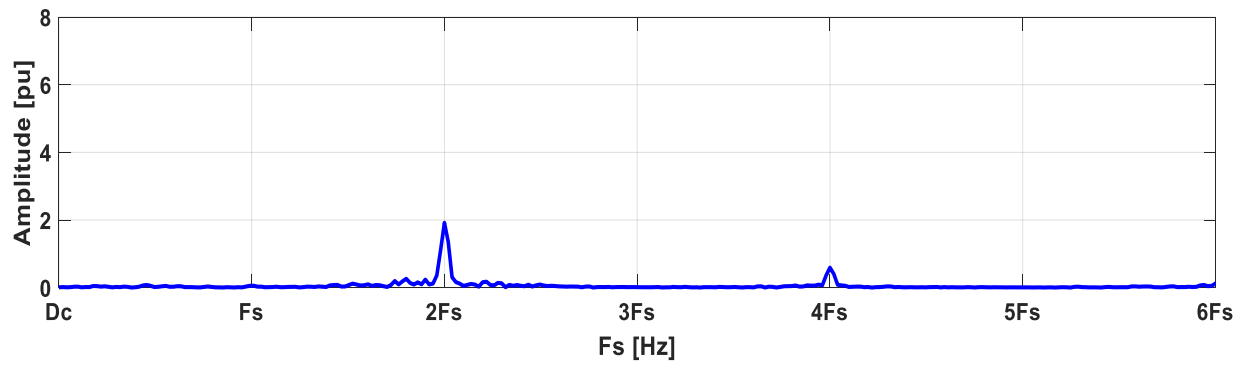
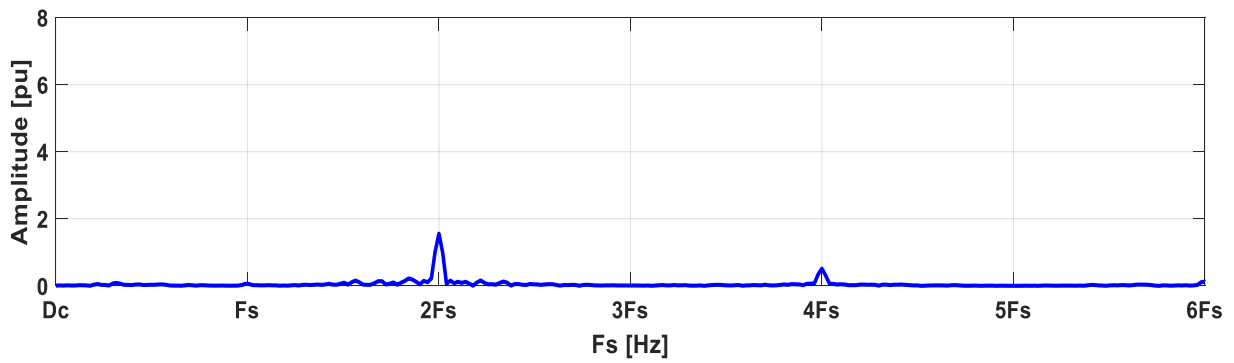
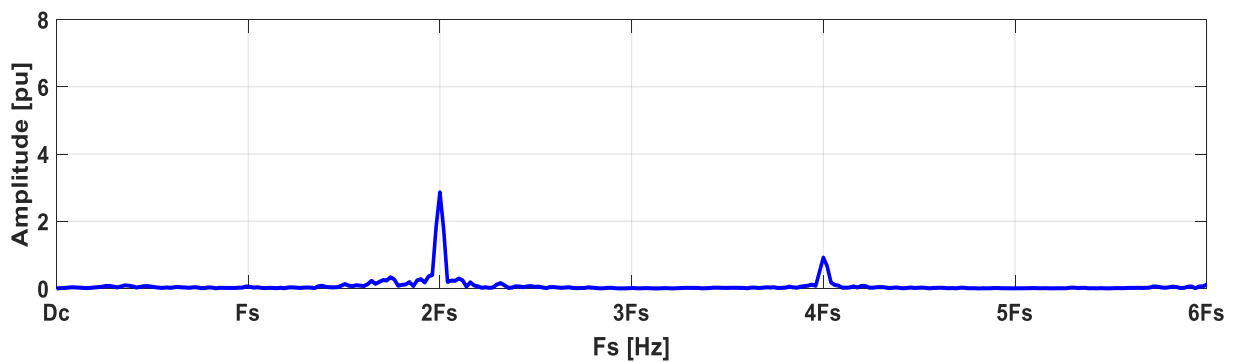
18 turns**32 turns**

Figures. III .6. Spectrum of theActive Power for different ITSCF, with $R_f = 4 \Omega$.

III.4.2. Reactive Power:

R=8Ω

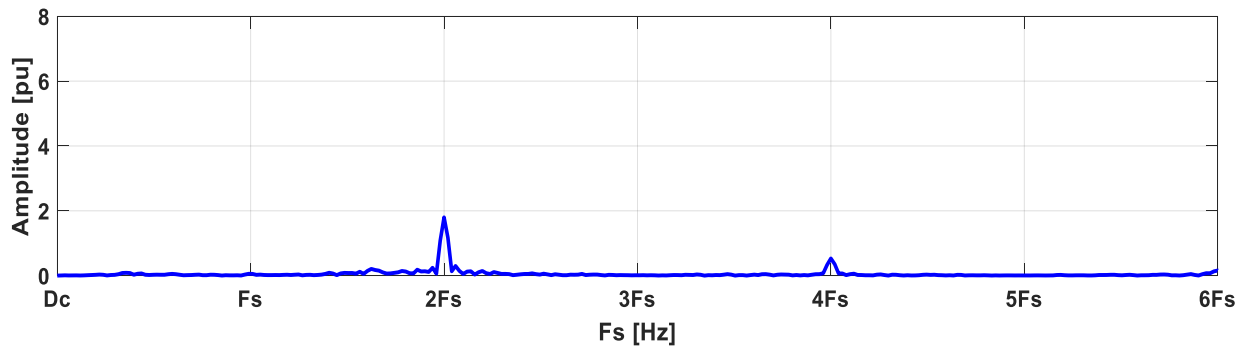
Healthy

08 turns**18 turns****32 turns**

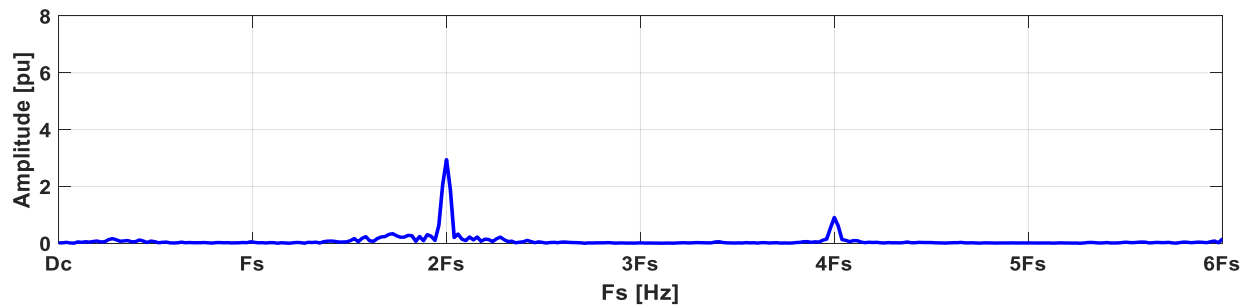
Figures. III .7. Spectrum of theActive Power for different ITSCF, with $R_f = 8 \Omega$.

R=4Ω:

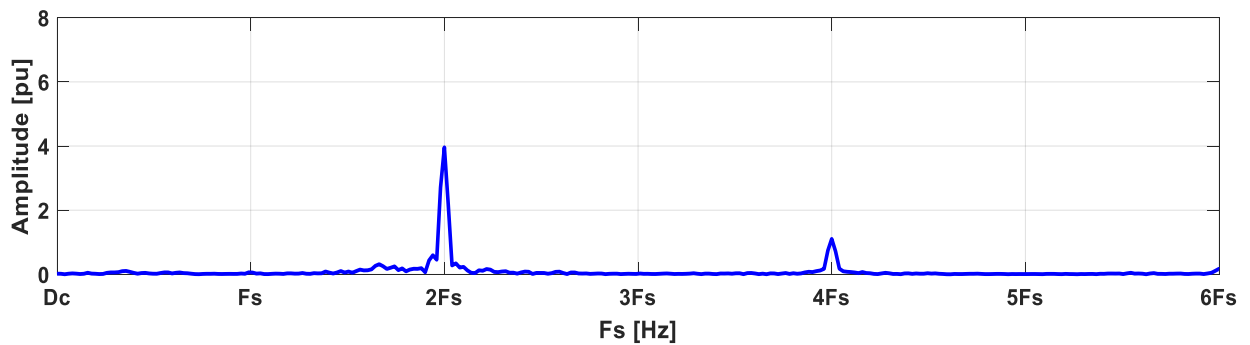
08 turns



18 turns



32 turns



Figures. III .8. Spectrum of theActive Power for different ITSCF, with $R_f = 4 \Omega$.

By studying the performance of the frequency components in the figures (III .5. III .6 , III .7 , III .8), the second and fourth harmonics are the components that can be relied upon for each of P and Q , and with different resistances ($R_f = 4 \Omega$, $R_f = 8 \Omega$) as they are affected by the variable short circuit cycles.

III.5. Conclusion:

The purpose of this chapter is to empirically test three methods, such as stator currents, Park Vector, and Active and Reactive powers approach , to analyze these methods and their impact For closed-loop control over wave forms.

General conclusion

General conclusion

Today synchronous machine occupies an important place in the world of industry thanks to its interest and structural simplicity due to its numerous uses in various applications, SynRM is one of the candidates we talked about because of the lack of rare earth elements, cheap cost, equivalent to the speed range at constant power, maximum torque per Ampere, SynRM efficiency, these motors have become an attractive option in traction.

The work presented in this thesis is part of the SynRM synchronous motor fault diagnosis. In this study , At the beginning of this work , we conducted a general study on the diagnostics of synchronous machines and focused on the stator for the SynRM , fault monitoring and description of the most common errors that may occur in the SynRM We have mentioned all the errors that may occur during its operation, the reasons that lead to such malfunctions and their consequences.

Then we mentioned the various detection methods currently used and also talked in general about the methods used in this work. Then we analyzed the stator malfunction of the SynRM through the various diagnostic methods and techniques most commonly used for error detection, such as signal approach , Finally, a brief theoretical review of SynRM control techniques is provided.



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