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Title:

Current Sensor Fault Tolerant Control of Permanent Magnet Synchronous Machine

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Dedication

I dedicate this thesis wholeheartedly to my dearest unbiological brother ***BEN DREF Mansour Djassem*** who showed his profound devotion and continually provided his moral, spiritual and emotional support when no one else did.

I dedicate it to my beloved father and mother, to my three sisters who showed me their kind words and encouragement to finish this study, to my two brothers, to the real friends who I had the chance to meet and love, and to each and every person who shared his words of advice.

Lastly, I dedicate this work to the almighty **Allah**, who guided me, granted me strength and power of mind, and provided me with protection, skills and a healthy life of relief and obedience. All of these, I offer to you.

Abderaouf

Dedication

To my precious Mother

To my beloved Father

To my dear sister and brothers

To my dear grandfather and family

To every true honest friend

To my cheerful cousins

To every person wishing me every success

And again, to my teachers of all levels.

I dedicate this work

Mohamed
Amine

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Abstract

To ensure the safety operation and service continuity of control systems, a control technique appeared called Fault-Tolerant Control (FTC). It enables the detection and isolation of faults, as well as the reconfiguration of the control system, to ensure continuity of service and to protect the healthy components from the effects of failing elements. Certainly, several works have been carried out on this subject in different fields of application, among them: the current sensors faults presented in the AC electric drives based on motors like Permanent Magnet Synchronous Motors (PMSMs). These kind of motors are widely used in the industry for variable speed applications due to their high performance reliability and power density. However, in order to achieve fault-tolerant control of current sensors faults , it is necessary to ensure the correct compromise between the detection of faulty sensors and the reconstruction of the currents. In this context, many methods have been proposed for the detection or estimation of three-phase stator currents. Apart from fault detection, current estimation is frequently based either on several cascaded observers, a current sensor and a voltage sensor in the converter DC bus, or an observer and a healthy line current sensor. In this work, the estimation of three-phase stator currents is approached by proposing a method based only on a single current observer, which ensures the estimation and correction of the three stator currents even in case of failure of all current sensors (Current sensorless). This method was then combined with a conventional fault detection and isolation circuit (FDI) and field oriented control (FOC), where the assembly is an active fault-tolerant control for current sensors. Another fault tolerant control method against current sensor faults based on a speed robust controller is named passive fault tolerant control (PFTC). Both methods proposed in this work were applied on an SPMSM. Promising results were obtained in simulation on Matlab/Simulink.

Keywords: Electric drives, PMSM, dq modeling, Vector control, Field oriented control, Space vector pulse width modulation, Active fault tolerant control, Passive fault tolerant control Current sensor, Observer, Fault detection and Isolation.

ملخص

لضمان سلامة التشغيل واستمرارية الخدمة في أنظمة التحكم، ظهرت تقنية تحكم تسمى "التحكم بسماحية العطب" (FTC). تتيح الكشف عن العطب وعزله، فضلا عن إعادة تشكيل نظام التحكم، لضمان استمرارية الخدمة وحماية العناصر المكونة السليمة من انعكاسات العناصر المكونة القاصرة. من المؤكد أن العديد من الأعمال نُفِّذَت بشأن هذا الموضوع في مجالات تطبيق مختلفة، من بينها: عيوب مستشعرات التيار الواردة في محركات التيار التي تعمل بنظام التيار المتناوب (AC) القائمة على محركات مثل المحركات المتزامنة ذات المغناطيس الدائم (PMSM) ، والتي استخدِمَت على نطاق واسع في الصناعة في تطبيقات السرعة المتغيرة نظراً لموثوقية أدائها وكثافة طاقتها العاليين. لكن من أجل تحقيق تحكم بسماحية العطب لمستشعرات التيار، من الضروري ضمان الحل الوسط الصحيح بين الكشف عن المستشعرات المعيبة وإصلاح التيارات. في هذا السياق، اقتُرِحت العديد من الطرق لاكتشاف أو توقع التيارات ثلاثية الطور للجزء الثابت. بغض النظر عن اكتشاف العطب، كثيرًا ما يعتمد توقع التيار إما إلى عدة مراقبين متسلسلين أو إلى مستشعر تيار ومستشعر جهد كهربائي في ناقل تيار مستمر للمحول أو مراقب ومستشعر تيار خطي سليم. في هذه الأطروحة، يتم التعامل مع توقع تيارات الجزء الثابت ثلاثية الطور عن طريق اقتراح طريقة تعتمد على متوقع تيار واحد فقط، مما يضمن توقع التيارات الثلاثة للجزء الثابت حتى في حالة فشل جميع مستشعرات التيار (لا مستشعرات التيار). ثم اقترنت هذه الطريقة بدارة كهربائية تقليدية للكشف عن العطب وعزله (FDI) والتحكم بالحقل الموجه (FOC) حيث تشكل هذه المجموعة تحكمًا بسماحية العطب الفعال لمستشعرات التيار (AFTC). توجد طريقة أخرى للتحكم بسماحية العطب غير الفعال لمستشعرات التيار مبنية على التحكم القوي للسرعة تدعى (PFTC). طُبِّق كلا التحكمين في تحمل العطب المقترح في هذه الأطروحة على محرك متزامن ذو مغناطيس دائم (SPMSM)، تم الحصول على نتائج مرضية في المحاكاة في برنامج Matlab/Simulink.

الكلمات المفتاحية: محرك كهربائي، محرك متزامن ذو مغناطيس دائم، نمذجة dq، التحكم في القوة الموجهة، التحكم بالحقل الموجه، تضمين عرض النبضة للفضاء المتجه، التحكم الفعال بسماحية العطب، التحكم غير الفعال بسماحية العطب، مستشعر تيار كهربائي، متوقِّع، الكشف عن العطب وعزله.

Résumé

Pour assurer la sûreté de fonctionnement et la continuité de service des systèmes de contrôle, une technique de commande est apparue nommée la commande tolérante aux défauts, en terme anglo-saxon Fault Tolerant Control (FTC). Elle permet la détection et l'isolation des défauts, ainsi que la reconfiguration du système de commande, pour assurer la continuité du service et protéger les éléments sain de la chaîne de commande des effets des éléments défaillants. Certes, plusieurs travaux ont été effectués sur ce sujet dans différents domaines d'applications, parmi eux: les défauts des capteurs de courant présentés dans les commandes électriques à courant alternatif basés sur des machines tels que les machines synchrones à aimant permanent (MSAP) qui ont été largement utilisés dans l'industrie pour les applications à vitesse variable en raison de sa fiabilité et de sa densité de puissance élevées. Cependant, afin de réussir une commande tolérante aux défauts des capteurs de courant, il faut assurer le bon compromis entre la détection des capteurs défaillants et la reconstruction des courants. Dans ce contexte, de nombreuses méthodes ont été proposées soit pour la détection ou l'estimation des courants triphasées statoriques. Mise à part la détection des défauts, l'estimation des courants est fréquemment basée soit sur plusieurs observateurs en cascade, un capteur de courant et un capteur de tension dans le bus continu du convertisseur, ou bien un observateur et un capteur de courant de ligne sain. Dans cette thèse, l'estimation des courants statoriques triphasées est abordée en proposant une méthode basée uniquement sur un seul estimateur, qui assure l'estimation des trois courants statoriques, même en cas de défaillance de tous les capteurs de courant. Ensuite, cette méthode a été associée à un circuit classique de détection et d'isolation des défauts et une commande orientée du champ, où l'ensemble constitue une commande active tolérante aux défauts des capteurs de courant. Une autre commande passive tolérante aux défauts des capteurs de courants basée sur un contrôleur robuste pour le régulateur de vitesse existe. Les deux FTC proposée dans cette thèse ont été appliquées sur une MSAP. Des résultats prometteurs ont été obtenus en simulation sur Matlab/Simulink.

Mots clés: commandes électriques, MSAP, commande de vecteur, commande orientée du champ, modulation d'impulsion en durée à vecteur spatial, commande active tolérante aux défauts, commande passive tolérante aux défauts, capteur de courant, estimateur, détection isolation des défauts.

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Current Sensor Fault Tolerant Control of PMSM

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List of Abbreviations

AC	Alternative Current
AFTC	Active Fault Tolerant Control
ASD	Adjustable Speed Drive
BLDC	Brushless Direct Current
CSD	Constant Speed Drive
CTA	Constant Torque Angle
DC	Direct Current
DSC	Direct Self-Control
EMF	Electromotive Force
FDD	Fault Detection and Diagnosis
FDI	Fault Detection and Isolation
FDIIR	Fault Detection, Isolation, Identification, and Reconfiguration
FDIR	Fault Detection, Isolation, and Reconfiguration
FR	Fault Reconfiguration
FTC	Fault Tolerant Control
IFAC	International Federation of Automatic Control
IGBT	Insulated Gate Bipolar Transistor
IM	Induction Machine
IPMSM	Interior Permanent Magnet Synchronous Motor
KVA	KiloVolt Ampere
MMF	Magnetomotive Force
MTPA	Maximum Torque Per Ampere
PCB	Printed Circuit Board
PFTC	Passive Fault Tolerant Control
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
RAMS	Availability, Reliability, Maintainability, and Safety
SM	Synchronous Machine
SPD	Stable power drive
SPMSM	Surface-Mounted Permanent Magnet Synchronous Motor
STD	Stable Torque drive
SVM	Space Vector Modulation
SVPWM	Space Vector Pulse Width Modulation
VFD	Variable Frequency Drive
VSD	Variable Speed Drive

General Introduction

Nowadays, the AC machines have been approved over the DC machines in industry applications because of their various advantages, like the durability since they do not have brushes as the DC motors do, the low power requirement for start-up which allows them to more evenly distribute their power and maintain a consistent level of power throughout their operation, controlled acceleration which means they allow for steady and controlled movement, and the high speed as they are known for being able to cope with and deliver high speeds making them suitable for a range of demanding industry applications, along with their high reliability [1]. One of the most popular AC machines is the Permanent Magnet Synchronous Motor (PMSM) in which this work is about.

The permanent-magnet synchronous machine (PMSM) drive is one of best choices for a full range of motion control applications. For example, the PMSM is widely used in robotics, machine tools, actuators, and it is being considered in high-power applications such as industrial drives and vehicular propulsion. It is also used for residential/commercial applications. The PMSM is known for having low torque ripple, superior dynamic performance, high efficiency and high power density [2]. Since the copper and iron losses are concentrated in the stator, cooling of machines through the stator is more effective. The lack of field winding and higher efficiency results in reduction of the machine frame size and higher power/weight ratio [3].

Control techniques for PMSMs classified mainly into scalar and vector control, The Scalar Control, called also volts/hertz, is the simplest method to control a PMSM, where the relationship between voltage or current and frequency are kept constant through the motors speed range. No control over angles is utilized, hence the name scalar control. The method uses an open-loop control approach without any feedback of motor parameters or its position which makes it easy to implement and with low demands on computation power of the control hardware. However, this method does not dedicate for high performance applications due to its slow response and torque; flux coupling existence [6].

The vector control of a PMSM, also known as field oriented control was proposed for the first time by K. Hasse (indirect field-oriented control) [7] and F. Blaschke (direct field-oriented control) [8] in 1972 to provide an independent control of torque and flux in similar way to the separate excitation DC machine. The vector representation of the motor quantities makes it valid to work in both steady and dynamic conditions; this achieves a good transient response. In the control algorithm of FOC based on the transformation to the synchronous frame, all quantities appear as DC quantities. Yet, the FOC has some drawbacks as in the coordinates transformation which needs the flux angle that cannot be directly measured, in addition, the sensitivity to the variation of the machine parameters.

Direct Torque Control (DTC) is another method that guarantees a separated flux and torque control. It was introduced by Takahashi and Nagochi in the middle of 1980s in Japan [9], and also in Germany by Depenbrock under the name of Direct Self-Control (DSC) [10]. In contrast to FOC, this control is completely done in stationary frame (stator fixed coordinates). Furthermore, DTC generates the inverter gating signals directly through a look up switching table that is no modulator is needed.

The control of AC machines is essential, it is important to know and study the different failures that can affect each element of the control loop of these machines to the extent possible to predict the faulty states of the system's components to ensure the service continuity and protect the healthy components, as well as the human user.

A fault is an unauthorized deviation of at least one system characteristic property or parameter from the standard condition [11]. Three main types of faults can be indicated in the case of drive systems, starting with power electronics faults, which can be divided into power semiconductor faults and DC bus faults [12–14]. Another type of failure are mechanical faults [15,16,17] and electrical faults [18–20] concerning the motor. The last type are sensors faults, which may concern mechanical or electrical variables [21]. Each of the mentioned failures is the object of research by scientists dealing with fault tolerant control. Inappropriate measurements can affect the whole drive system. Sensors are subject to various faults. It is estimated that 14.1% of all system failures are caused by sensor faults [6]. Since sensors (including current sensors) are critical drive system components in the case of permanent magnet synchronous motors (PMSMs), fault detection, localization, and tolerant control schemes of current sensors are presented for high-fault-tolerance drives. Generally, three-phase current sensors are used in high-power inverters; nevertheless, failure of current sensors degrades the performance and reliability and even leads to the breakdown of the vector control system.

When a failure occurs in a system, the activation of an alarm is essential, but the emergency shutdown of the system is not always the best course of action. Therefore, simultaneous reconfiguration of this is required to allow uninterrupted operation which is the aim of fault tolerant control technique. Fault detection and fault diagnosis (FDD), in general, are based on diagnostic signals measured by sensors or on process variables and states observed by a human operator. The automatic processing of measured signals requires analytical knowledge, while the evaluation of observed variables needs human expert knowledge, which is called heuristic knowledge [22, 23, 24]. Analytical knowledge consists of different methods, from simple rules defining limit values of measured signals to complex methods of signal analysis, such as: spectral analysis, filtration, state and parameter estimation, mathematical models, etc. while Heuristic knowledge includes human observation and inspection, heuristic specific values in the form of noises, vibration, colors, smells, temperature, wear and tear, etc.. Thus signals and variables measured and observed together with analytical and heuristic knowledge enable the isolation of fault symptoms and next the proper fault diagnosis. Taking into account the way of generating symptoms, two main fault detection methods can be distinguished: Process-model-based fault detection methods (comparative methods) and signal-model-based fault detection methods (direct methods) [24].

About 20 years ago, together with the Fault Detection and Diagnosis (FDD) methods, also the Fault Tolerant Control (FTC) was developed [23, 25–27]. The FTC aims to ensure the continuous system functionality, even after fault occurrence. FTC systems possess the ability to detect component failures automatically, using suitable FDD methods. They are capable of maintaining overall system stability and acceptable performance as long as the controlled system can be safely stopped for maintenance or repair. In other words, a closed-loop control system which can tolerate component malfunctions, while maintaining desirable performance and stability properties is said to be a Fault Tolerant Control System (FTC).

Redundancy is the duplication of critical components or functions of a system with the intention of increasing reliability of the system, usually in the form of a backup or fail-safe, or to improve actual system performance. Redundancy can be categorized into two types. The direct redundancy, where actual physical hardware redundancy is available. Or analytical redundancy (software redundancy), where instead of having multiple sensors that measure the same signal, an observer is used to provide an estimate of the signals of interest. i.e, there is no actual additional hardware implemented, instead some algorithm or mathematical model or observer runs in the control computer [28]. This is desirable in many systems especially in the case of AC motor drives to increase the reliability and the performance of the system.

FTC systems based on software (analytical) redundancy are generally divided into two classes: passive and active FTCs.

Passive FTCs (PFTCs) asre based on robust controller design techniques and aim at designing a single, robust controller that makes the closed-loop system insensitive to unexpected faults. Under faulty conditions a process continues operation with the same structure and parameters of the controller [25-27]. This approach does not require on-line faults detection and is therefore computationally more attractive

Active FTCs (AFTCs) are based on controller reconfiguration or selection of a few predesigned controllers. This technique requires a fault detection and diagnosis (FDD) system that realizes the task of detecting and localizing the faults if they occur in the system**.** AFTCs systems use dedicated detectors or special state or parameter observers [23, 25-27] to identify failure condition. The choice of the proper topology and fault tolerant control algorithm depends on the system requirements and used components. Designing such a system is a complicated and complex issue because of the need to ensure its stable operation after a component failure, while maintaining full or partial functionality at the required performance level of the whole process.

Current sensors are a key element for a successful control of an electrical drive system, which is why in this work, two fault tolerant control techniques to these faults along with simulations of permanent magnet synchronous motor while the occurrence of different current sensor faults was done and well achieved regarding results.

Chapter I

State of the Art & Generalities

Part one: Background about electric drives

1.1 Introduction

Most technical and industrial developments are based on energy, of which the mechanical form is the final form of energy in every motion. The mechanical energy is available in nature as hydro or wind energy. However, in these latent forms its use is very limited, because its transportation, distribution and control are not practical. The usual way is to convert the energy into a suitable form for transportation and to make it available in final form for the consumer. The best method of doing this is to use the electrical energy as an intermediate stage [29].

In the first part of this chapter, a definition of electric drives, their importance and applications are stated. Then, the components of an electrical drive are to be stated in details.

1.2 Electric drives: General overview

Electrical energy is an intermediate stage in the conversion of natural energy forms to mechanical energy, which is the final form in every motion. Electrical motors play the main role in this conversion. Different types are available to fit almost every application with the general advantages of high efficiency, wide power range and control simplicity [1]. Power electronics is the other main component of electrical drives, which combines power semiconductors of high rating with digital hardware to convert and control the electrical power in a suitable way. The synergetic effect of this combination with modern control strategies makes electrical drives the leader among the other drive types.

1.2.1 Electric drives definition

- **Drive:** A combination of prime mover, transmission equipment and mechanical working load is called a drive as shown in **Fig.1.1**. It may have prime mover as diesel engine or petrol engine, steam engines, gas or steam turbine, electric motors or hydraulic motors for providing mechanical energy to have the motion control.
- **Electrical drive:** It is an electromechanical system that employs an electric motor as the prime mover. It is designed to convert electrical energy into mechanical energy to impart motion to different machines and mechanisms for various kinds of process control. The system employed for motion control is called an electrical drive [30].

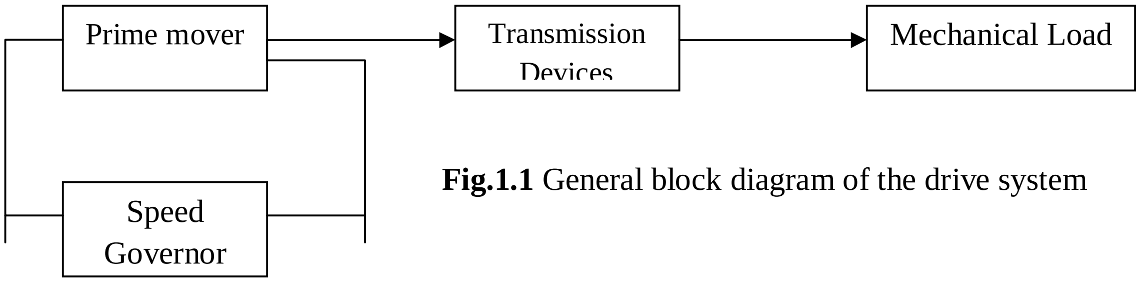


Fig.1.1 General block diagram of the drive system

1.2.2 Importance of electric drives

As mentioned before, the best method in the energy conversion is to use the electrical energy as an intermediate stage. This preference has three main reasons. The first reason is the efficient generation of electrical energy from primary energy forms. The second reason is the simple transportation and distribution of the electrical energy. In electrical form the energy can be transported with low losses over long distances and can be distributed very simply at relatively acceptable costs. Finally the last reason is the easy conversion of electrical energy into mechanical energy by using electrical machines which have been the workhorses of industry for many years. Electrical drives, involving different types of electrical motors, turn the wheels of industry. In an industrialized country, more than 60% of the generated electrical energy is used in motor drives [31].

On the other hand, the increasing electrical energy demand causes tremendous concern for environmental pollution. There is no doubt that energy savings will improve these side effects considerably. It has been estimated that even in developed industrialized countries, roughly 20% of energy can be saved by using more efficient control schemes for electrical drives [32].

1.2.3 Electric drives classification

The development of different kinds of electric drives used in industry may be divided into three stages: individual drive, group drive and multi-motor drive.

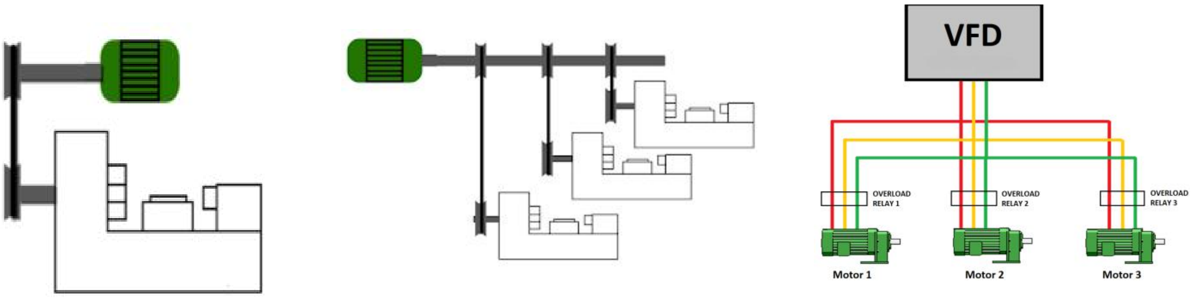


Fig.1.2 Types of Electric Drives:

(a) Individual drive **(b)** Group drive **(c)** Multi-motor drive

- **Individual drive:** A single motor is dedicated to a single load. It is the most common drive and can be found in various applications like: electric saw, drill, disk drive, etc.
- **Group drive:** Or line shaft drives the oldest type of drives. A single motor drives equipment through a common line shaft or belt. It is inflexible and inefficient as you cannot change the speed of each load alone.
- **Multi-motor drive:** In this complex type of drive, separate motors are provided for actuating different parts of the driven mechanism. Ex: cranes, drives used in paper mills, rolling mills etc.

In addition to the previous general classification, these drives are further categorized based on the different parameters which are demonstrated in the following figure.

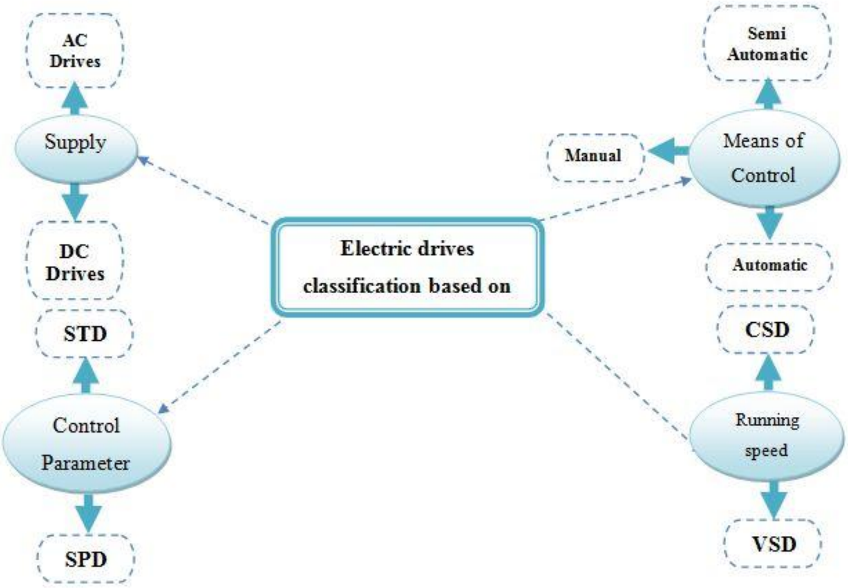


Fig.1.3 Another classification of electric drives

1.2.3.1 Electric drives based on supply

- **AC drives:** they convert the AC supply to DC using a rectifier and invert it back from the DC to the AC using an inverter to run the AC motors.
- **DC drives:** they only convert the input AC supply to the DC using converter circuit based on rectifier to run the DC motors.

1.2.3.2 Electric drives based on running speed

- **Constant speed drives (CSD):** is a type of transmission that takes an input shaft rotating at a wide range of speeds, delivering this power to an output shaft that rotates at a constant speed, despite the varying input.

- **Variable speed drives (VSD):** refers to either AC Drives or DC Drives whereas variable frequency drive (VFD) refers to AC drives only. VFDs vary the speed of an AC motor by varying the frequency to the motor. VSDs referring to DC motors vary the speed by varying the voltage to the motor.

1.3 Modern AC Electric drives

AC drives are used to drive the AC motor. In industrial terms, AC drive is also called as variable frequency drive (VFD), variable speed drive (VSD), or adjustable speed drive (ASD). Though there are different types of VFDs (or AC drives), all of them work on the same principle by converting fixed incoming voltage and frequency into variable voltage and frequency output. The frequency of the drive determines how fast motor should run while the combination of voltage and frequency decides the amount of torque that the motor generates.

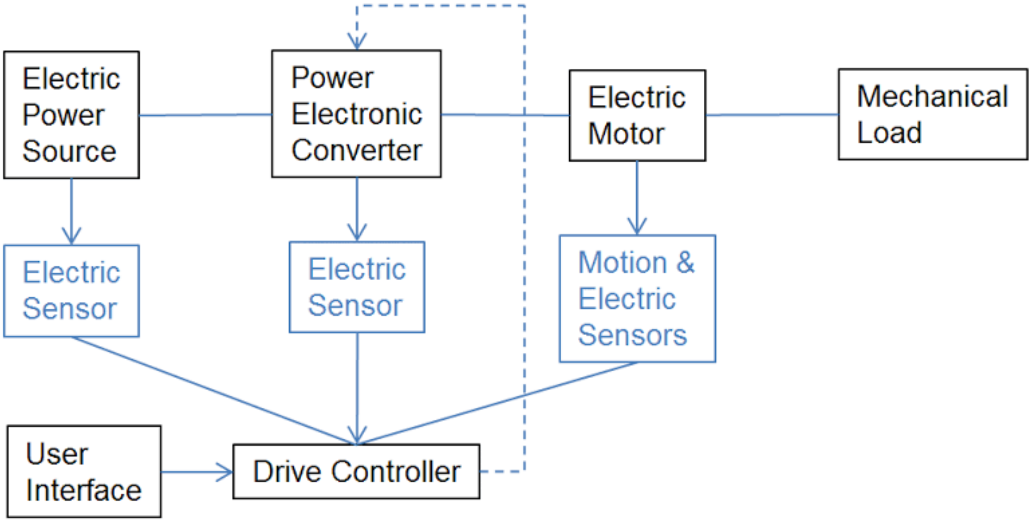


Fig.1.4 The basic diagram of a variable speed electrical drive system

Fig.1.4 shows the basic structural diagram of a variable speed electrical drive system which generally has the following components:

- A device that transforms electrical power into mechanical power.
- A device that control the electrically driven assembly to obtain motion of specific form (linear or rotary motion) and response to a master controller.
- A device that converts mechanical energy and impart it to the actuating mechanism (reducers and other intermediate gearing).

The drive system components are:

1.3.1 Power Source

Power Source provides the energy to the drive system (energy requirement for the operation the system). It could be:

- **Regulated** (e.g: utility)
- **Unregulated** (e.g. : renewable energy)

Unregulated power sources must be regulated for high efficiency by the use of power electronic converters. It could be also:

- **DC source**: Batteries, fuel cell, photovoltaic....etc
- **AC source**: Single- or three- phase utility, wind driven generators.

1.3.2 Power modulator

Power modulators regulate the power flow from source to the motor to enable the motor to develop the torque speed characteristics required by the load [30]. In electric drive systems, the power modulator used is:

Converters: Use power devices to convert uncontrolled valued to controllable output, they provide adjustable voltage/current/frequency to control speed, torque output power of the motor. The various type of converters are:

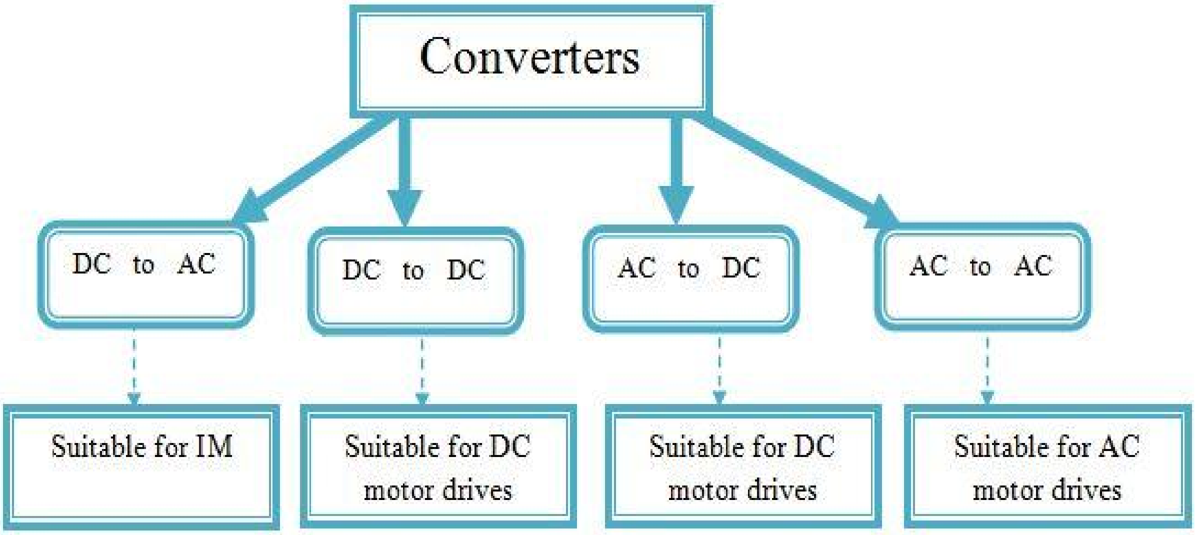


Fig.1.5 Different types of converters in an electric drive system

1.3.3 Controller

The control unit implements the control strategy governing the load and motor characteristics and to do so, the input to the power converter is controlled by the controller either using an analog or a digital controller.

1.3.4 Sensing unit

The sensing unit is used to sense the particular drive factor such as speed, motor current. This unit is mainly used for the operation of closed loop otherwise protection. It mainly uses sensors with different types as shown in the following figure.

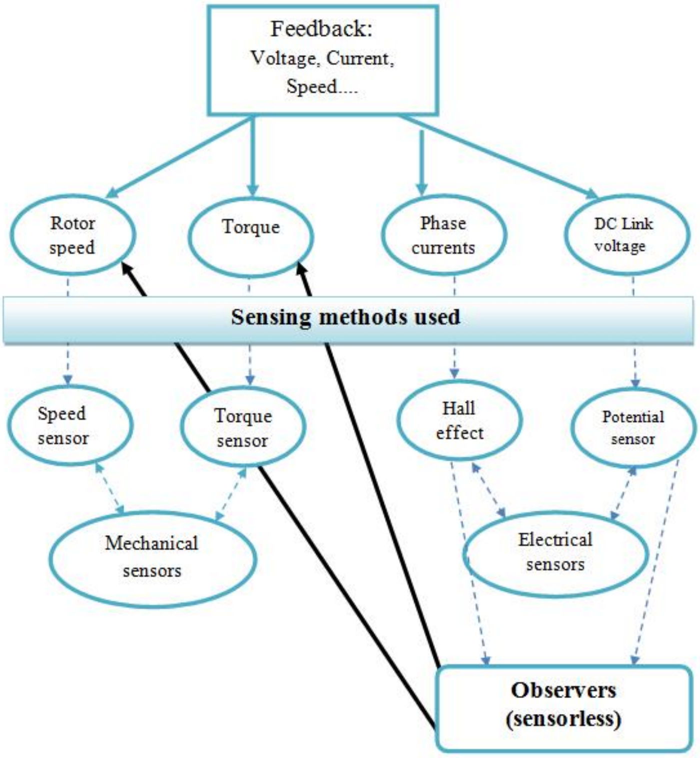


Fig.1.6 Different sensing methods in electric drives systems

1.3.5 Electric motor

It is the actual energy converting machine, the most commonly used electrical motors for the various control applications in electric drives are illustrated in **Fig.1.7**. The following points must be given high importance for the selection of motors [30]:

- Nature of the mechanical load driven and type of source available.
- Matching the speed torque characteristics of the motor with that of the load.
- Cost, thermal capacity, efficiency and environment.

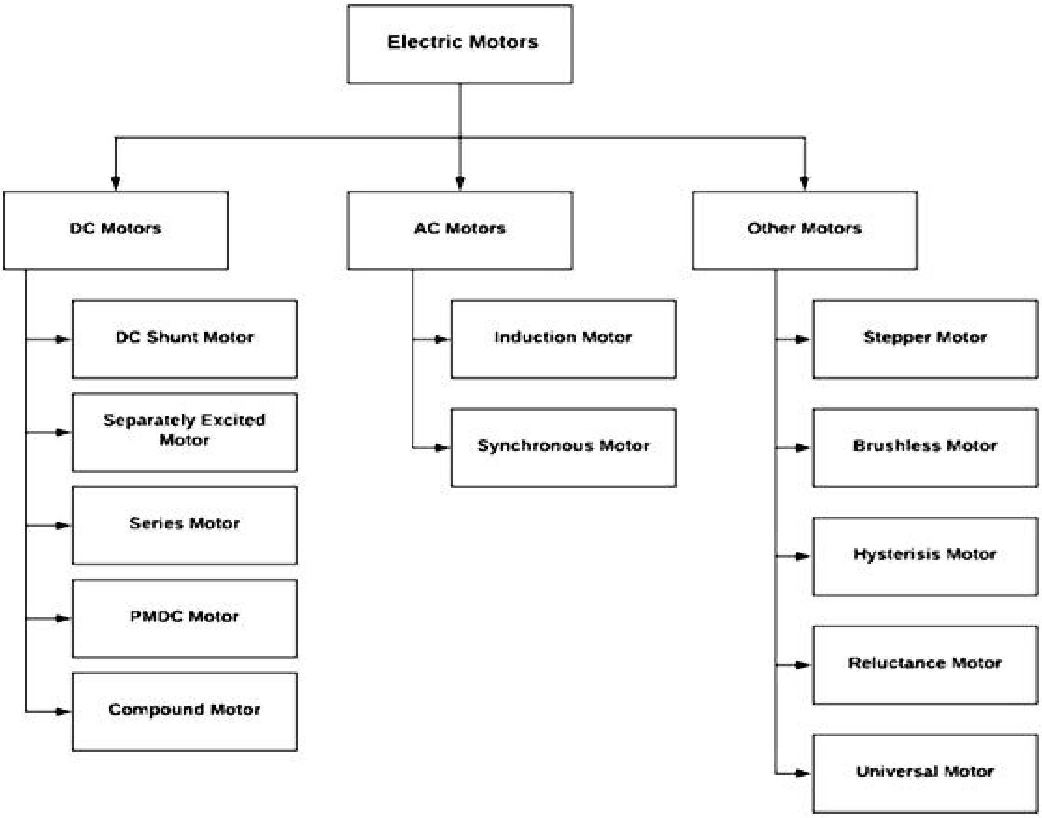


Fig.1.7 Different electrical motors used in electric drives

1.3.5.1 Benefits of AC motors

As the motor to be used in this work is an AC motor "PMSM". Here are some of the main benefits of these kind of motors to bear in mind:

- **Durable:** AC electric motors are extremely durable because unlike most DC motors, they do not have brushes; Brushes can become worn down easily and creates the need for more regular maintenance [35].
- **Low power required for start-up:** Which means AC motors can distribute their power more evenly and can maintain a consistent level of power throughout their operation. It also decreases the chance of burn out, which can occur when a motor becomes overworked at start-up.
- **Controlled acceleration:** Within AC motors, it means they allow for steady and controlled movement, which is key for many demanding applications across the globe. It also reduces wear and tear as speeds are not increasing and decreasing abruptly, therefore placing less pressure on the motor [35].
- **High speed:** AC motors are known for being able to cope with and deliver high speeds, making them suitable for a range of demanding industry applications.

1.3.6 Mechanical load

The mechanical load torque can be classified to:

- **Active Load torques:** Type of load torques which has the potential to drive the motor under equilibrium conditions. They usually retain sign when the drive rotation is changed.
- **Passive Load torques:** Type of load torques which always opposes the motion and change their sign on the reversal of motion.

The components of load torques are:

- **Friction Torque (T_F):** It is the equivalent value of various friction torques referred to the motor shaft.
- **Windage Torque (T_W):** When a motor runs, the wind generates a torque opposing the motion. This is known as the winding torque.
- **Mechanical Torque (T_m):** It is the torque required to do useful mechanical work.

Since the nature of torque depends on the type of loads and it may change with the change in the loads mode of operation. The following figure (**Fig.1.8**) shows the characteristics of different types of loads.

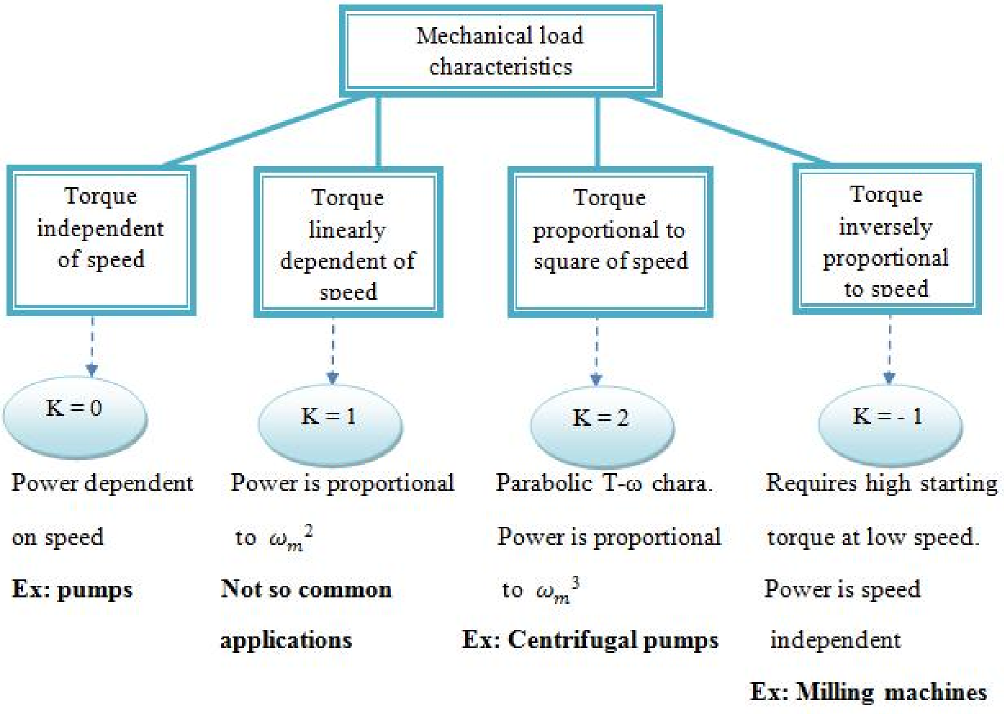


Fig.1.8 Characteristics of different types of mechanical loads

1.4 Advantages of AC electric drives

Due to the increasing use of these drives, many advantages count for them as follows:

- AC drives provide the most energy efficient means of capacity control.
- AC drives have the lowest starting current of any starter type.
- AC drives reduce thermal and mechanical stresses on motors and belts.
- AC drives provide high power factor, lower KVA, helping alleviate voltage sags and power outages
- AC drives basic operation is simple and reliable and guarantee saving in space and cost with low maintenance cost and long life.

Part two: Fault tolerant control (FTC)

1.1 Introduction

The performance of machines and equipment of technological systems degrades as a result of aging and wear, which decreases performance reliability and increases the potential for different faults. Actuator faults reduce the performance of control systems and may even cause a complete breakdown of the system. Erroneous sensor readings are the reason for operating points that are far from the optimal ones. In many fault situations, the system operation has to be stopped to avoid damage to machinery and humans. Due to the simultaneously increasing economic demands and the requirements of the system safety and reliability, the correct diagnosis of abnormal condition plays an important role in the maintenance of industrial systems. Fault tolerant control combines diagnosis with control methods to handle faults in an intelligent way. The aim is to prevent simple faults to develop into serious failure and hence increase the availability and reduce the risk of safety hazards.

At the beginning of this part of this chapter, a brief presentation of the types of faults that may appear in the AC machines drives as well as safety process operation to be done. As fault tolerant control is subject to this thesis, the different types of fault tolerant commands as well as the techniques of fault detection and isolation will be presented also.

1.2 Dependability

As mentioned earlier, electric drive systems are massively prone to faults due to aging and/or difficult operating conditions. This can lead to significant failures, degradation of system performance, which causes other faults in the control loop, or even cause the complete shutdown of the entire loop, which is not recommended in some areas as pumping stations and even unacceptable in other areas like aeronautics. Indeed, the availability and security of systems represent an essential challenge for their functional viability and compliance with regard to the operational safety standards. That is why it is necessary to develop control strategies that must be capable of an automatic accommodation when a fault occurs to maintain an acceptable level in the performance of the system and meet the required level of safety at the same time.

1.2.1 Concept and terminology

Since the twentieth century, man has realized that authority and power will belong to the one who will dominate the industry in all its varieties. As a result, fast advance in technology and integration of electrical systems in the industry has never stopped growing. The complexity of industrial systems has made the monitoring operation increasingly necessary and important to ensure the safe operation of these systems. This concept has progressed over time (**Table.1.1**) to encompass different disciplines and approaches that are applicable today in all fields.

Year	Progression	Areas of application
1940-1950	Discovery of a probabilistic approach (concept of reliability)	Electronics in aeronautics, defence and nuclear energy.
1960-1970	Generalization of the probabilistic approach (maintainability)	Components:mechanical, hydraulic, electrical, …
1980	Development of methods of analysis, computer software, Software-modelling,… Constitution of databases	Use of the resulting approach for control of any industrial risk type.
Today	This concept covers reliability, the availability, maintainability, safety, sustainability, diagnosis, detection of faults, isolation of faults, etc.	Almost all domains.

Table.1.1 Summary of the progress of the concept of dependability [41]

Dependability (Operational safety), also known as failure science, involves assessing potential risks, predicting the occurrence of failure science, ensure continuity of service and attempt to minimize the consequences of catastrophic situations when they occur (**Fig.1.9**).

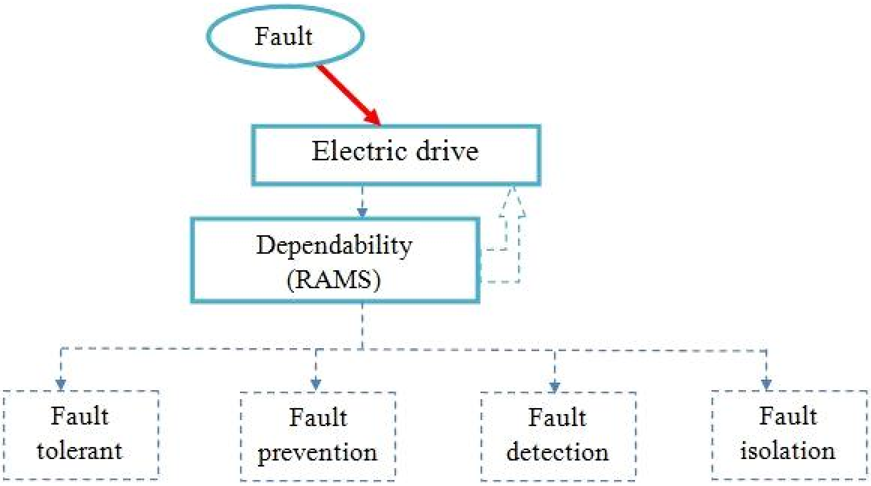


Fig.1.9 Dependability of an electric drive

Dependability can be broken down into three elements as they will be stated next [42].

- **Attributes**

Attributes are qualities of a system. These can be assessed to determine its overall dependability using qualitative or quantitative measures: (Availability, Reliability, Safety, Integrity and Maintainability).

- **Threats**

Understanding of the things that can affect the dependability of a system, three main terms must be defined by the use of The IFAC technical committee:

Fault: an unpermitted deviation of at least one characteristic property or parameter of the system from the acceptable/usual/standard condition [11].

Error: difference between the desired and actual performance or behavior of a system. In control systems, it is defined as the difference between a set point and the process value.

Failure: a permanent interruption of a system’s ability to perform a required function under specified operating conditions [11].

- **Means**

Means can be defined as the ways to increase a system's dependability; four means have been identified so far:

Prevention: fault Prevention deals with preventing faults being incorporated into a system.

Removal: removal during development requires verification so that faults can be detected and removed before a system is put into production. Once systems have been put into production a system is needed to record failures and remove them via a maintenance cycle.

Forecasting: fault forecasting predicts likely faults so that they can be removed or their effects can be circumvented by the use of previous recorded data and good estimations.

Tolerance: the ability of a controlled system to maintain control objectives, despite the occurrence of a fault. A degradation of control performance may be accepted. Fault-tolerance can be obtained through fault accommodation or through system and/or controller reconfiguration.

1.2.2 RAMS

Traditionally, dependability for a system incorporates availability, reliability, maintainability but since the 1980s, safety and security have been added to measures of dependability [42]. Which are known as "RAMS". The relation between these terms is shown in **Fig.1.10** and are stated next.

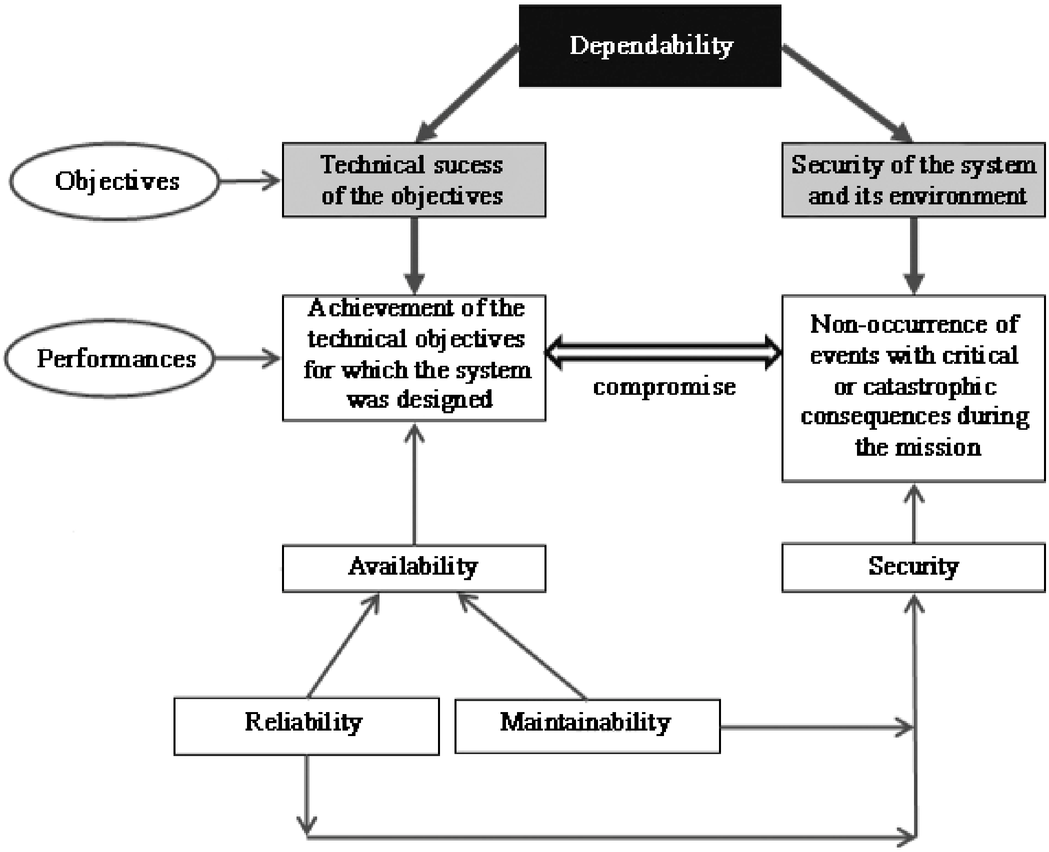


Fig.1.10 Logic and impact of dependability

- **Availability**: The probability that an item will operate satisfactorily at a given point in time when used under stated conditions in an ideal support environment.
- **Reliability**: the ability of an equipment or system to function without failure. Reliability describes the ability of a system or component to function under stated conditions for a specified period of time.
- **Maintainability**: the ability of a component or system to be put back into service (repaired) within a stated time interval by given procedures and resources.
- **Security**: the ability to pose no danger to persons, equipment or environment and also not to cause accidents and catastrophic damage.

1.3 Faults in AC machines (PMSM) drives

During the last decade, the use of AC machines never stopped growing. Therefore, the control of these machines has become essential. In this regard, it is important to know and study the different failures that can affect each element of the control loops of these machines to the extent possible to predict the faulty states of the system to ensure the continuity of the service and protect the healthy components, as well as the human user. In this section, various faults in the components of the AC machines (PMSM) drives are listed.

1.3.1 Classification of faults

A fault can generate a degradation of one of the functions performed by elements in the system or the whole system itself that is unavailable due to failure. The faults can be divided into four types according to their severity: minor fault, severe fault, critical fault and catastrophic fault.

First, the minor fault is a fault that can affect the proper functioning of the system by causing negligible damage to the system itself or to its environment. It does not reduce the ability of the device to perform its required functions. Second, the severe fault that can also be called a major fault is a fault that risks reducing the ability of the device to perform its required function. Third, the critical fault results in the loss of an essential function of the device with an impact on the environment, the system or people. Fourth, the catastrophic fault results in the loss of one or more essential functions of the system in causing significant damage [43].

AC electrical drive systems are subject to different faults whose consequences significantly depend on the fault location [44, 45]. Faults may affect the electrical motor (the actuator) [15-19], sensors (components) [21], supply and the static converters (components) [12–14]. A classification of faults that can affect the three main parts of the drive system is presented in the following subsections and summarized in **Table.1.2.**

Fault location					
Electrical Motor Faults		Sensor Faults		Power Electronics Faults	
Electrical faults	Mechanical faults	Electrical sensors (voltage and current)	Mechanical sensors (position and speed)	Supply faults	Power converters (AC/DC DC/AC)
•Windings short circuit •Insulation deterioration •Broken bars and rings in the rotor	•Rotor eccentricity •Misalignment •Bearings faults •Resonance	•Total failure •Noise •Offset •Saturation	•Total failure •Periodic interruptions of signal •Offset	•Loss of one or more phases •unbalance of phase or voltage	•Open circuits •short circuits •Aging of Components •Capacitor faults in the DC link

Table.1.2 classification of faults in AC electrical drive systems [55]

1.3.1.1 Faults in the PMSM (Actuator faults)

Permanent magnet synchronous machines (PMSM) have been widely used in various applications due to their characteristics. However, PMSMs are not immune to faults, which requires an efficient and reliable condition monitoring method to avoid downtime or even catastrophic failures. Electrical and mechanical faults of motors constitute a significant part in the PMSM drive system faults [15-20]. Electrical faults are connected with the stator windings of the motor (constitutes about 37% of all PMSM faults). The stator winding failures occur due to insulation stresses, inter-turn short circuits or even short-circuits of phase windings. In the case of PMSM rotor faults (they about 10% of all PMSM faults) are connected mainly with deterioration of permanent magnets performance or their mechanical displacements or vibrations, rotor eccentricity, broken bar...etc. Mechanical faults in the electrical motors are connected with the quality of mechanical connection between the driving motor and a load machine. It could be: bearing faults (they are close to 41 % of all PMSM faults), rotor eccentricity, misalignment, clutch or gear failures [47]

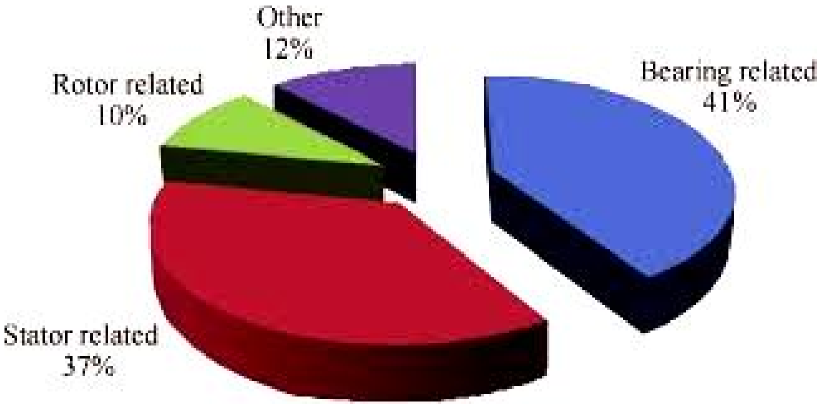


Fig.1.11 Distribution of faults in PMSMs [47]

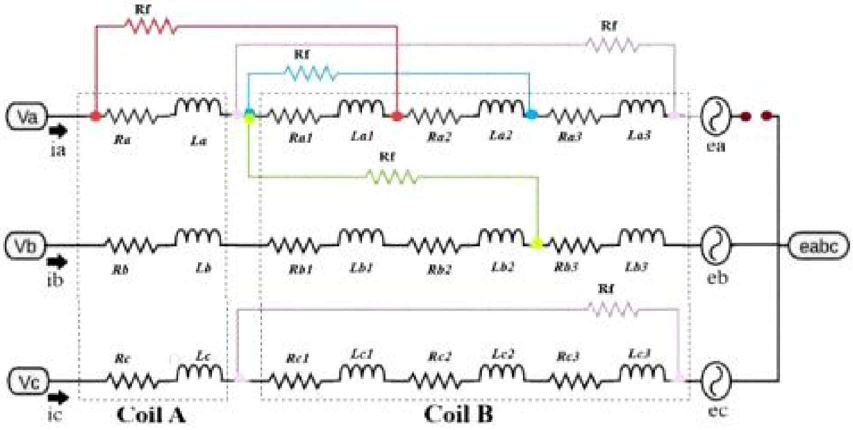
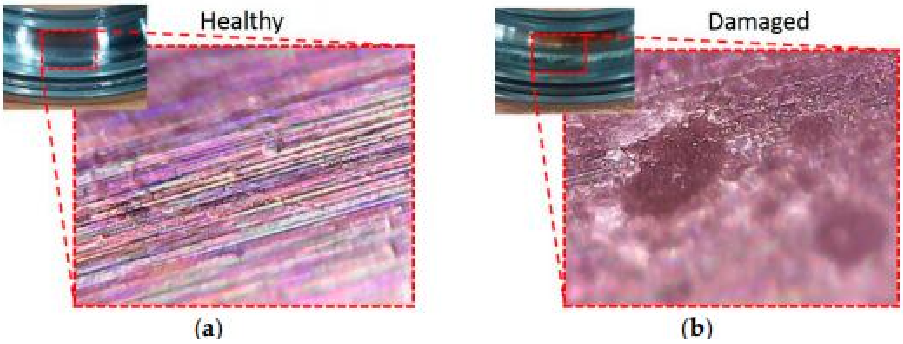


Fig.1.12 Various stator fault types [48]



(a) (b)

Fig.1.13 Microscopic view of the bearing: (a) healthy bearing (b) damaged bearing [49]

1.3.1.2 Faults in sensors (Components faults)

The sensors are key components of a closed-loop system, ensuring information required for the generation of control signals from the controller. A sensor is a device that transforms a physical size observed in a usable electrical signal. The presence of a sensor fault in a closed loop means a bad image of the measured physical value, therefore the controller signals will be ineffective. Unfortunately, the sensors are very sensitive to faults caused by:

connection problems, under-voltage in the power battery, noise, offset and positive or negative gain faults, or total sensor loss [50]. The incorrect measurements delivered by a sensor are usually caused by faults on one hand in the core of the sensor (corrosion, cracks and rupture of the core) and on the other hand by other changes in the magnetic characteristics of the nucleus due to changes in temperature, but also by changes in the orientation of the induced magnetic field in the sensor [51] without forgetting human errors. It is estimated that 14.1% of all system failures are caused by sensor faults [6].

1.3.1.3 Faults in the power converters (Components faults)

In vector controlled AC motor drives which are supplied from voltage-source inverters that mostly use power switches based on the insulated-gate bipolar transistors (IGBTs) due to their high efficiency, high switching frequency and relatively short-circuit current handling capability. Among various types of failures in electric motor drive applications, power converter faults make up about 80 % [52,53]. There are many kinds of faults in power converters such as a power semiconductor device (21 %), solder (13 %), DC-link capacitor (30 %), printed circuit boards (PCB) (26 %), sensor, etc [52]. Thus power device modules failures compose 34 % of power converter faults.

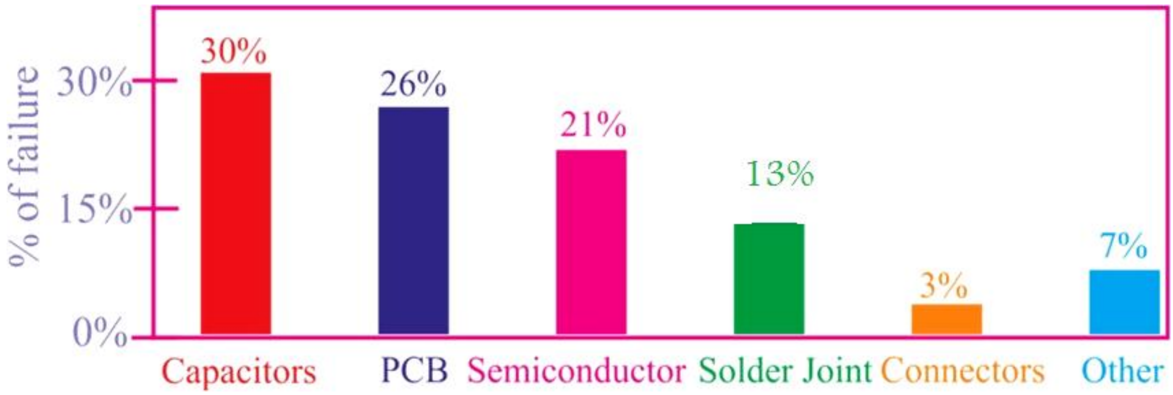


Fig.1.14 Faults in the power converters - Components faults - [52]

The power device faults can be divided into two cases: short-circuit faults and open-switch faults. A short-circuit fault can occur due to several reasons, such as the wrong gate voltage, overvoltage, avalanche stress, or temperature overshoot. Short-circuit faults are difficult to handle because of an abnormal over-current which can cause serious damage to other parts is produced within a very short time. In addition, the period between the fault initiation and failure is very short.

An open-switch fault occurs due to the lifting of a bonding wire caused by thermal cycling. An extremely high collector current may also cause open-switch faults. The open-switch fault leads to a current distortion. The open-switch fault does not cause serious damages, compared to short-circuit faults, but it does degrade the performance of overall converter systems. This type of switch failure should be detected and compensated, as it causes big stator current values and high transients in electromagnetic torque which could damage the drive [52, 54]. Another expected fault which occur in electric drives, is DC bus link failure. The electrolytic capacitors are predominantly used in DC-links because of their low cost. However, they have some undesirable properties such as sensitivity to temperature, frequency and low reliability resulting in their finite lifetime and high failure rate due to a wear-out degradation failure.

1.4 Fault tolerant control

Fault-tolerant control (FTC) is a strategy that has the ability to maintain required or degraded performance and operational safety of an identified system under well-defined conditions. The purpose of the FTC is not only to ensure the continuity of service and the operation of a well-known system in the presence of faults, but also to ensure the protection of the healthy components and elements of the system and prevent their degradation, knowing that the FTC is carried out according to a well-defined specification.

1.4.1 Fault detection and fault diagnosis methods

Damage preventing can be realized using different actions, like: protection, equipment redundancy or analytical redundancy and technical diagnosis methods. The protection systems belong to classical methods of monitoring of industrial processes. The alarms raised due to limit values crossing cause an automatic action of protection systems. This method works well in steady state of the process or if the monitored variables does not depend on the operating point. However, faults are detected rather late and a detailed fault diagnosis is mostly not possible and are effective only for a rather large sudden fault or a long-lasting gradually increasing fault [24]. The reliability of the industrial processes can be also obtained using the equipment redundancy which, however, raises significant costs and requires extension of control, measuring and supervising equipment. Such solutions are applied only in critical industrial processes. The other method of system reliability increasing is application of analytic redundancy, which is based on an additional diagnostic information obtained using mathematical models, methods of control theory and signal processing.

1.4.2 Redundancy

Redundancy is the duplication of critical components or functions of a system with the intention of increasing reliability of the system, usually in the form of a backup or fail-safe, or to improve actual system performance. Redundancy can be categorized into two types: direct redundancy and analytical redundancy.

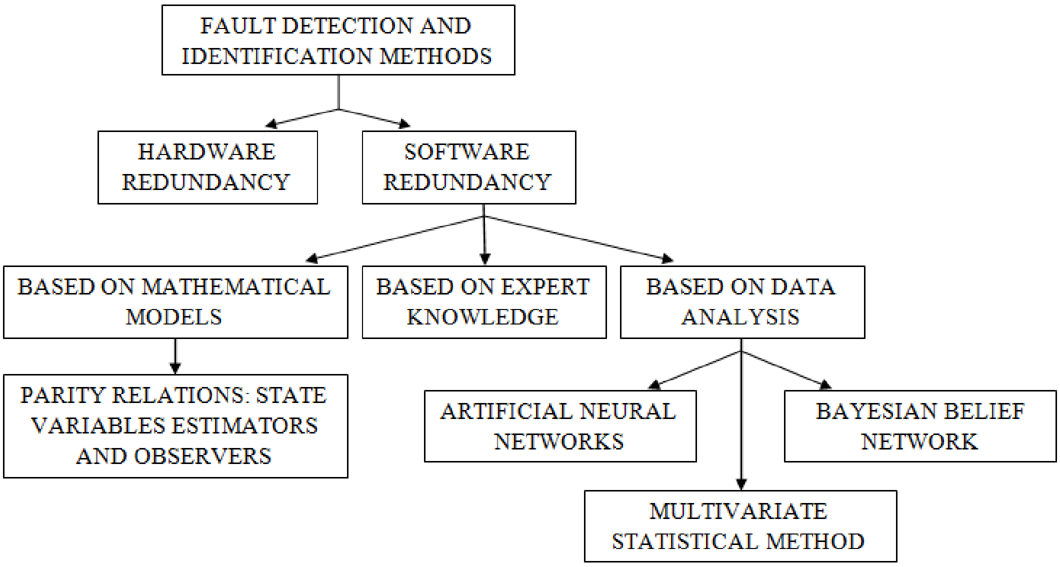


Fig.1.15 Fault detection and identification methods based on redundancy

In direct redundancy, actual physical hardware redundancy is available. In terms of sensors, two or three sensors that measure the same quantity is called double and triple redundancy. In normal operation, only one sensor is sufficient, however, two or three sensors are required to ensure reliable measurements in the case of faults. In terms of analytical redundancy or software redundancy, instead of having multiple sensors that measure the same signal, an observer that provides an estimate of the signals of interest provides analytical redundancy. There is no actual additional hardware implemented, instead some algorithm or mathematical model or observer runs in the control computer. This is desirable in many systems especially in the case of AC motor drives to increase the reliability and the performance of the system.

1.4.3 Basic fault detection methods

Fault management and damage preventing can be realized nowadays using advanced methods of automatic supervision and technical diagnostics, e.g. fault detection and fault diagnosis methods, which use modern control systems theory methods, mathematical models and signal models of the processes, identification, estimation methods, computational intelligence and informatics. For a well fault management and damage preventing, Fault tolerant control passes by three important stages :

Fault detection: detection of the failure in the controlled plant and time of the detection.
Fault isolation: determination of the type, location and time of the failure.
Fault identification: determination of the fault size and its evolution in time.

Fault detection and fault diagnosis (FDD), in general, are based on diagnostic signals measured by sensors or on process variables and states observed by a human operator. The automatic processing of measured signals requires analytical knowledge, while the evaluation of observed variables needs human expert knowledge, which is called heuristic knowledge [22, 23, 24]. Analytical knowledge consists of different methods, from simple rules defining limit values of measured signals to complex methods of signal analysis. While heuristic knowledge includes human observation and inspection. The process history (e.g. previous failures), experience with maintenance and repair operations constitute additional sources of heuristic information. Thus signals and variables measured and observed together with analytical and heuristic knowledge enable the isolation of fault symptoms and next the proper fault diagnosis. The diagnosis process is illustrated in **Fig.1.16**.

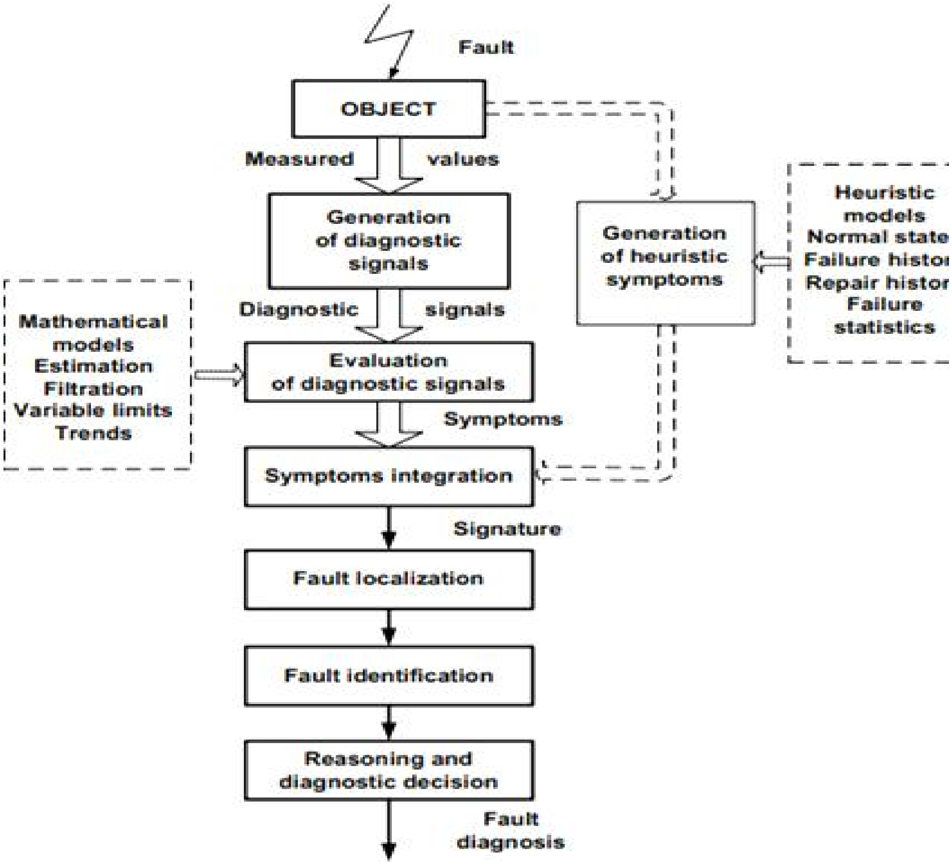


Fig.1.16 The main idea of the diagnostic process [55]

Taking into account the way of generating symptoms, two main fault detection methods can be distinguished [24]:

1- Process-model-based fault detection methods (comparative methods): are based on dependencies between different measurable signals. Its basic structure is illustrated in **Fig.1.17**. Based on the measured input signals U and output signals Y, the detection methods generate residuals r, parameter estimates Ó or state estimate Ẍ , which are called features. By comparison with normal features (nominal values), changes of features are detected, leading to analytical symptoms s. In the simplest solution, the diagnostic signal is calculated as a difference between output signals measured in the object and those obtained from the model (residuum r). If the object operates normally ("healthy" object), this value oscillates around zero. For a faulted object this value is much greater, which confirms the fault.

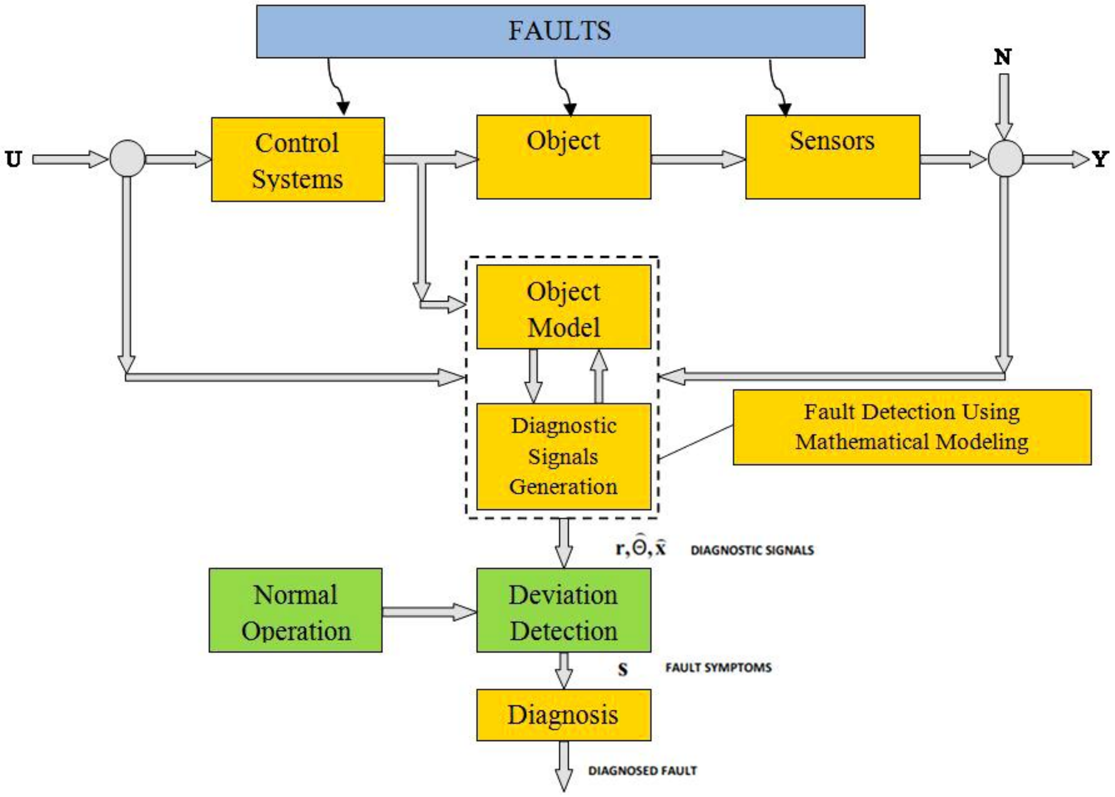


Fig.1.17 The general scheme of process-model-based fault detection system

Different mathematical models can be applied in process-model-based methods, such as: state estimators or observers, Kalman filters, parity equations [23,24]. Comparative methods are closely connected with redundancy methods, and because mathematical models have an analytical form, this type of redundancy are called analytical redundancy.

2- Signal-model-based fault detection methods (direct methods): they rely on the analysis and inspection of selected physical variables which are characteristic for a given object and thus are sometimes called direct methods. In the simplest solutions the limits of credibility or limit values (thresholds) are checked. In other solutions more advanced signal analysis methods, such as: Fourier analysis, spectral analysis are applied, depending on the type of the analyzed signals [24,56]. The general scheme of the diagnostic procedure conducted with signal-model-based fault detection methods is presented in **Fig.1.18**.

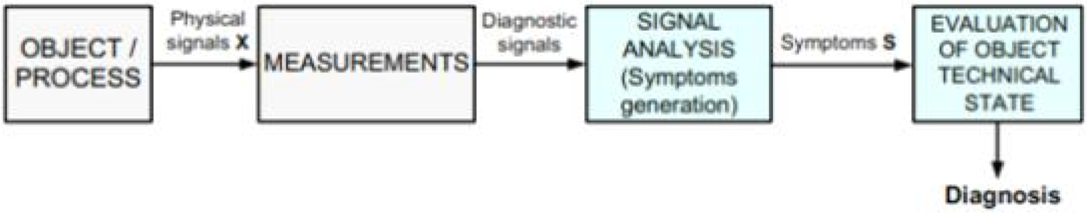


Fig.1.18. An illustration of signal-model-based fault detection methods [55]

1.4.4 Fault tolerant control: General Overview

About 20 years ago, together with the Fault Detection and Diagnosis (FDD) methods, also the Fault Tolerant Control (FTC) was developed [23, 25–27]. FTC systems possess the ability to detect component failures automatically, using suitable FDD methods. In other words, a closed-loop control system which can tolerate component malfunctions, while maintaining desirable performance and stability properties is said to be a fault tolerant control system (FTC).

The general scheme of the FTC system is presented in **Fig.1.19**. The FDD system constitutes a part of the FTC system and is responsible for providing the supervision system with information about the location and severity of any fault. The supervision system can take a suitable action and can reconfigure the sensor set and/or actuators to isolate the faults, and tune or adapt the controller to accommodate the fault effects [23, 25, 27].

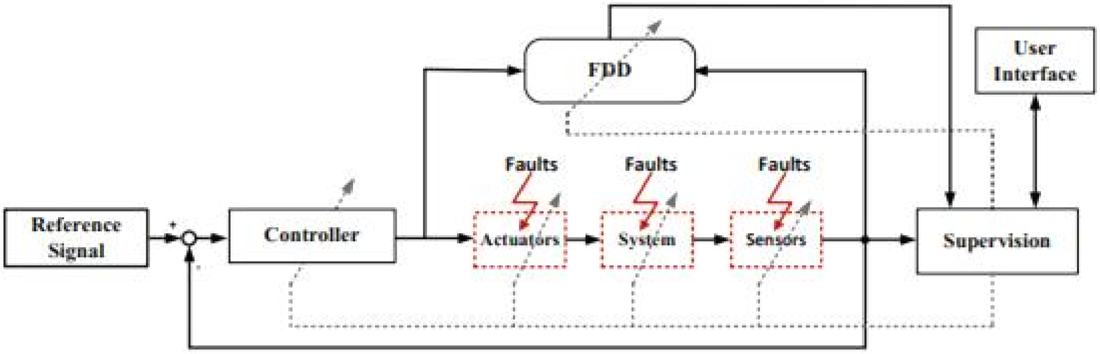


Fig.1.19 The general scheme of FTC system with supervision subsystem [55]

The hardware (equipment) redundancy, is attractive from the viewpoint of full system functionality after fault occurrence, but it raises significant costs and requires duplication of control, measuring and even actuator equipment. Such solutions are applied only in critical industrial processes or installations. FTC systems based on software (analytic) redundancy are generally divided into two classes: **passive** and **active FTCs** as shown in **Fig.1.20**.

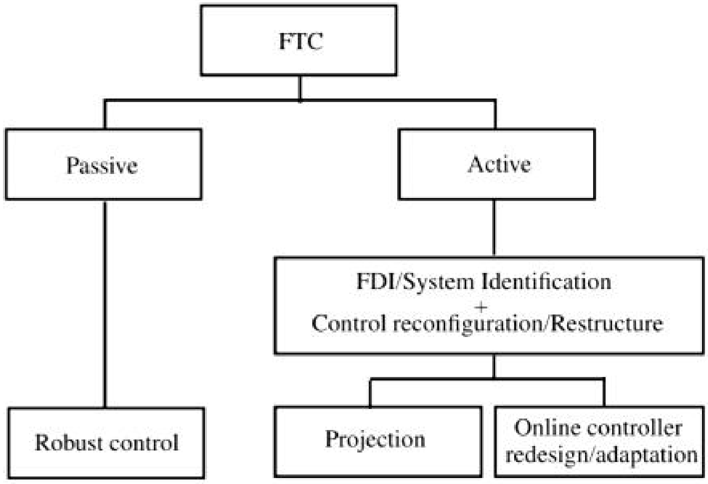


Fig.1.20 Types of FTC systems based on software redundancy

1.5 Passive Fault tolerant control

Passive FTCs (PFTCs) are based on robust controller design techniques and aim at designing a single robust controller that makes the closed-loop system insensitive to unexpected faults. Under faulty conditions, a process continues operation with the same structure and parameters of the controller [25–27]. The general scheme of PFTC is presented in **Fig.1.21**.

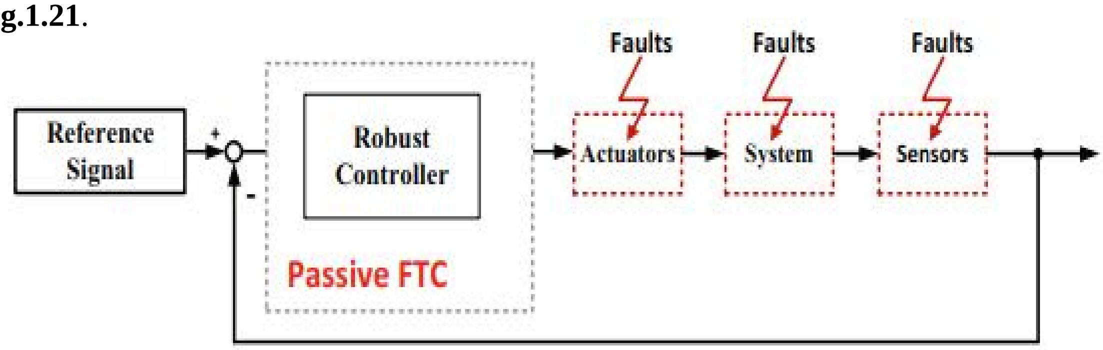


Fig.1.21 The scheme of a passive FTC system [55]

This approach does not require on-line faults detection and is, therefore, computationally more attractive. The controller design for PFTC is based on advanced control techniques, such as: adaptive theory, predictive control concepts or artificial intelligence.

The applicability of PFTC is very limited due to its serious disadvantages [26]:

- A very selective subset of possible faults can be considered in the design of a PFTC system, usually those faults that do not have a significant effect on the system operation of the system can be treated in this way, while only under such condition the controller robustness to faults can be achieved.
- An increased robustness to certain faults can be achieved at the expense of decreased nominal performance of the system. Since faults happen rather rarely, it is not reasonable to significantly degrade the fault-free performance of the system only to achieve some insensitivity to a restricted class of faults.

Still, PFTCs have some advantages too. One of them is the fact that a fixed controller has relatively reasonable hardware and software requirements. Another advantage is lower complexity compared to active FTC systems [23, 26, 27].

1.6 Active Fault tolerant control

Active FTCs (AFTCs) are based on controller reconfiguration or selection of a few predesigned controllers. This technique requires a fault detection and diagnosis (FDD) system that realizes the task of detecting and localizing the faults if they occur in the system. The structure of an AFTC system with a FDD unit is presented in **Fig.1.22**.

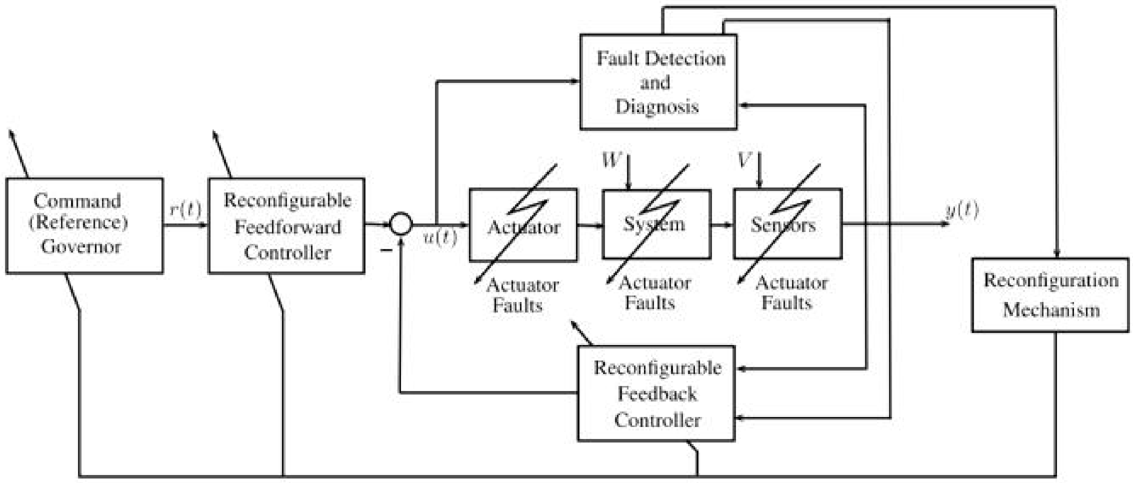


Fig.1.22 The scheme of active FTCs [55]

The FDD part uses input-output measurement from the system to detect and localize the faults. The estimated faults are subsequently passed to a reconfiguration mechanism that changes the parameters and/or the structure of the controller in order to achieve an acceptable post-fault system performance which guarantees the continuity of the system. AFTC systems use dedicated detectors or special state or parameter observers [23, 25–27] to identify failure condition. The choice of the proper topology and fault tolerant control algorithm depends on the system requirements and used components.

Designing such a system is a complicated and complex issue because of the need to ensure its stable operation after a component failure, while maintaining full or partial functionality at the required performance level of the whole process.

1.7 Chapter conclusion

This chapter was divided into two parts. The first part was a brief background about electric drives and their components. The second part dealt with fault tolerant control by first introducing the dependability and RAMS concepts, then the different faults types in AC drives and their effectiveness on the system's performance and security were listed. Finally, the fault tolerant control technique based on software redundancy was introduced including its two types (AFTC, PFTC) based on process-model-based detection technique.

Chapter II

Modeling & Vector Control of PMSM

2.1 Introduction

Currently, permanent magnet synchronous motors (PMSMs) are widely used for industrial application. The reasons are their advantages, such as a high efficiency factor, minimal size and weight parameters, low rotor inertia (resulting in a high speed of response), high reliability, significant life expectancy [2,3]. In addition, control circuits of such motors are simpler than those of other AC machines. Over the last years, the widespread use of PMSM was high due to significant price decrease in magnetic materials with high specific magnetic energy values (alloys *Ne2Fe14B*, *Sm2Co17*, etc.) used in its rotor construction [20]. Efficient operation of PMSM as part of VFDs demands a careful choice of the control system suitable for the completion of a given objective. There are many ways of designing a PMSM control system. The concept of vector control is common for modern high performance AC motor control techniques [5].

At the beginning of this chapter, an overview about the permanent magnet synchronous motor (PMSM) is going to be done. Then the mathematical models which are expressed either in a fixed three phase (abc) frame or in a rotating (d, q) frame in order to describe its dynamic behavior. Next, the field oriented control with space vector modulation (FOC-SVM) technique is going to be covered along with a simulation to be performed using Simulink at the end.

2.2 Synchronous motor drives

Modern synchronous motor drives are becoming more attractive with the advancement in material and control technologies; there are many types of synchronous motors like: wound-field, permanent magnet, and reluctance synchronous motors. The synchronous motor has found wide applications in the constant speed drives domain and are also widely used in variable speed drives with inverter-fed variable frequency supplies. The following figure illustrates the different synchronous motors used for synchronous motor drives applications.

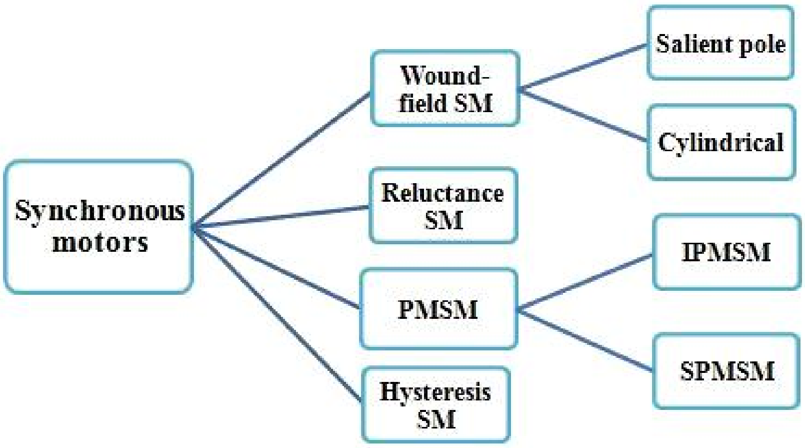


Fig.2.1 The classification of synchronous motors

2.2.1 Applications, advantages and disadvantages of PMSMs

Variable speed drives changed the field of motors which is used in such drives till the last decade. The induction motor and direct current motor have dominated as mechanical energy conversion devices but now they are being replaced by brushless DC motors (BLDCs) and PMSMs in the category of power application which ranges between 0-5 kW.

- **Application of PMSM in electric vehicles**

The dependence of fossil fuels has been step by step growing within the beyond century notwithstanding the famous fact that the resources of such fuels are restrained. It is now widely familiar that one of these demand growth is not always sustainable. Stimulated not only by the destiny supply concerns however also by way of the concerns of overexploitation of fossil resources the hobby in electric powered and hybrid automobile programs has been developing rabidly in recent years. Low energy consumption and high operating efficiency are provided by permanent magnets.

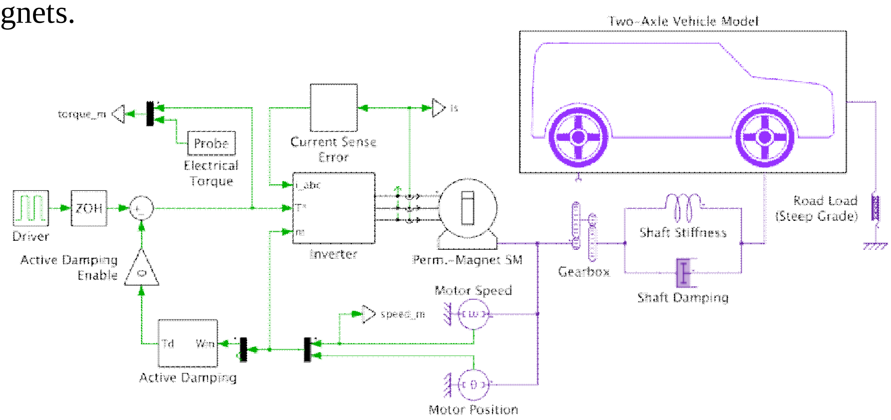


Fig.2.2 Electric Vehicle with Active Damping Algorithm [38]

The fuel consumption of PMSM is very low, so it is used in green vehicles. The awareness of green and electric vehicle improves the PMSM. Permanent magnet synchronous motor were an increasing number of utilized in electric vehicle applications owing their high efficiency, excessive power density, compact structure and rapid dynamic response. High power to volume ratio and high efficiency are achieved by permanent magnet motors.

- **Advantages of PMSMs over induction motors**

Modern permanent magnet synchronous motors may operate near unity power factor and have a large pull-out torque for a given frame size [37]. In PMSM, there is no provision for rotor side excitation control. The control is done entirely through the stator terminals. In low power applications, field excitation can be provided using permanent magnets, thus dispensing with the field winding losses, dc source, brushes and slip rings [39].

The PMSM is more suitable than induction motor, owing to the synchronous machine having interesting advantages, among which are [57]:

- Higher efficiency and more reliable and less noisy.
- Higher power density and high power factor with ability to maintain full torque at low speeds.
- The structure of the rotor is greatly simplified, which is convenient for maintenance and improves the stability of operation.
- The overall weight and volume are significantly reduced for a given output power, PMSM can be as much as one third of most AC motor sizes, which makes installation much easier.
- Heat is efficiently dissipated, the Joule losses are smaller due to absence of rotor currents.

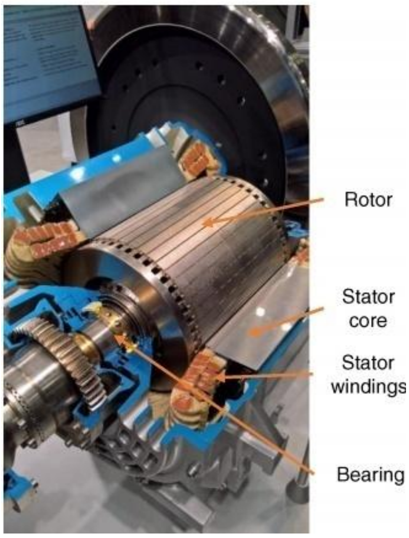


Fig.2.3 Construction of IM

- **Advantages of PMSMs over BLDCs**

As discussed in the previous section, PMSMs have come across as a better alternative to AC induction motors. The BLDC has also replaced the brushed DC motors. There is no major difference in control systems of BLDC and PMSM motors since both of them belong to the family of permanent magnet AC machines, except the nature of the drive current and the detection of the rotor position.

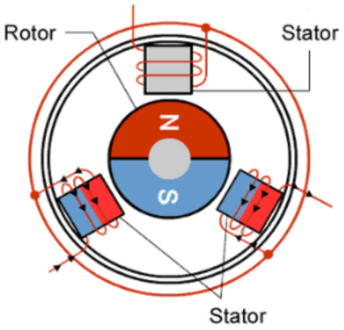


Fig.2.4 Construction of BLDC motor

In a BLDC motor, the rotor position is usually detected by a set of 3 HALL effect sensors. The commutation is achieved through a six-step process. This results in small breaks in commutation which in turn causes torque ripples (periodic increase/decrease in torque output of the motor) at the end of every step. The PMSM motor in contrast, requires only one HALL effect sensor as the commutation is continuous. Hence, the rotor position is monitored at every instance and is measured by the sensor and passed on to the PMSM motor controller solution.

One of the advantages of PMSM motor is the absence of torque ripple, which makes these motors more efficient than BLDCs and considering that the PMSMs has [57]: Higher power density, Less noise and smaller size. The ability to be used in hazardous environment.

- **Disadvantages of PMSMs**

On the other hand, PMSM has the following disadvantages:

- Most PMSMs require a drive to operate; as they cannot run without a drive. Moreover, some incorporate a squirrel cage in the rotor for starting; these are known as line-start or self-starting PMSMs.
- Complex control, demagnetization of the rotor magnet due to ageing.
- Reduction of torque production due to demagnetization of rotor magnet.

In addition, the PMSM have a short constant-power region owing to their rather limited field weakening capability, resulting from the presence of the permanent magnet field. It is clear that with the recent technological advances it is now possible and attractive to implement robust and powerful nonlinear controllers to reduce energy consumption and to improve performance under a wide range of power-speed operating domains.

2.3 PMSM Construction

PMSMs are kind of synchronous motors in which permanent magnet is used as rotor to create field poles, no field winding is wound on the rotor. The basic construction of PMSM is the same as that of synchronous motor. The only difference lies with the rotor. Field poles are created by using permanent magnets mounted on the rotor core [46]. Since the introduction of *Samarium-Cobalt* and *Neodymium-Iron-Boron* magnetic materials in the 1970s. SM with permanent-magnet excitation in the rotor have been displacing the dc motor in many high performance applications.

2.3.1 Permanent magnet materials

The property of the permanent magnet and the choice of suitable materials are crucial in the design of the permanent magnet machines [20]. The choice of permanent magnets is essential since they intervene a lot in the torque that can be expected from the actuator. Their performance often goes hand in hand with their cost [20], *Samarium-Cobalt* and *Neodymium-Iron-Boron* magnetic materials are mostly used since these materials are materials with high permeability (*it is the measure of magnetization that a material obtains in response to an applied magnetic field*), and high coercivity (*it is a measure of the ability of a ferromagnetic material to withstand an external magnetic field without becoming demagnetized*). Moreover, *Neodymium-Iron-Boron* is mostly used due to its ease of availability and cost effectiveness.

The physical characteristics of the PMSM are associated with its rotor and stator structures as illustrated in **Fig.2.5** and **Fig.2.6** respectively.

2.3.2 Stator of PMSM

The Stator is composed of a three-phase wound such that the Electromotive Forces (EMF) are generated by the rotation of the rotor field. Furthermore, the EMF can be sinusoidal or trapezoidal. This wound is represented by the three axes (a, b, c) phase shifted, one from the other, by 120 electrical degrees.

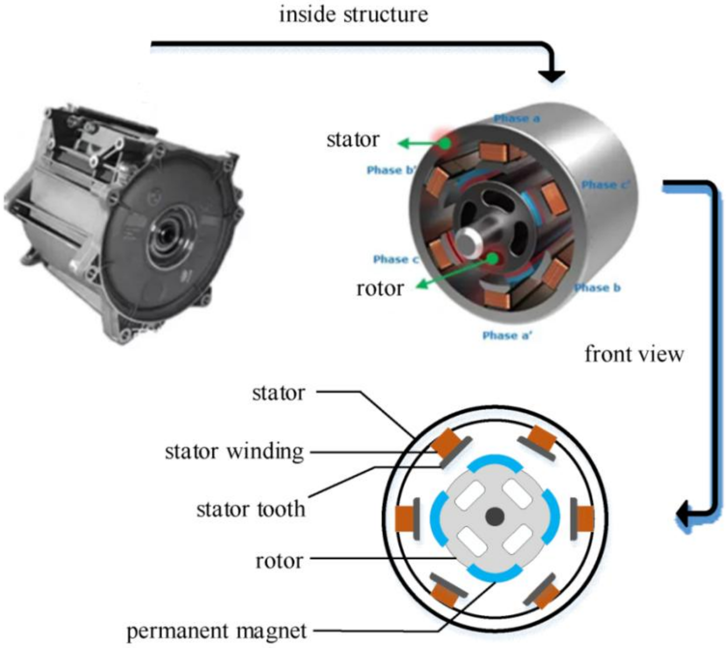


Fig.2.5 PMSM Stator construction

2.3.3 Rotor of PMSM

The Rotor incorporates permanent magnets (see **Fig.2.6**) to produce a magnetic field. Regarding winding, the permanent magnets have the advantage to eliminate the brushes, the rotor losses, and the need for a controlled DC source to provide the excitation current. However, the amplitude of the rotor flux is constant.

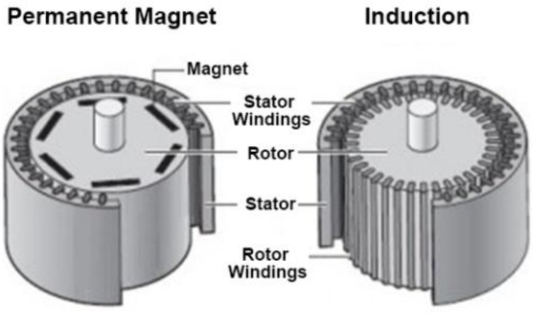


Fig.2.6 PMSM rotor versus IM rotor

On the other hand, there exist several ways to place the magnets in the rotor (see **Fig.2.7**) which will be covered in the next section.

2.3.4 Classification of PMSM

Following the magnet position, the PMSM can be classified into four major types [40]:

1. Surface mounted magnets type: The magnets are placed on the surface of the rotor using high strength glue. They present a homogeneous gap. The motor is a non-salient pole and the inductances do not depend on the rotor position (**Fig.2.7a**). The inductance of the d-axe is equal to those of the q-axe. This configuration of the rotor is simple to obtain. This type of rotor is the most usual. On the other hand, the magnets are exposed to a demagnetizing field. Moreover, they are subject to the centrifuge forces which can cause the detachment of the rotor.

2. Inset magnets type: The inset magnets are placed on the surface of the rotor. However, the space between the magnets is filled with iron (**Fig.2.7b**). Alternation between the iron and the magnets causes a salient effect. The inductance in the d-axe is slightly different from the inductance in the q-axe.

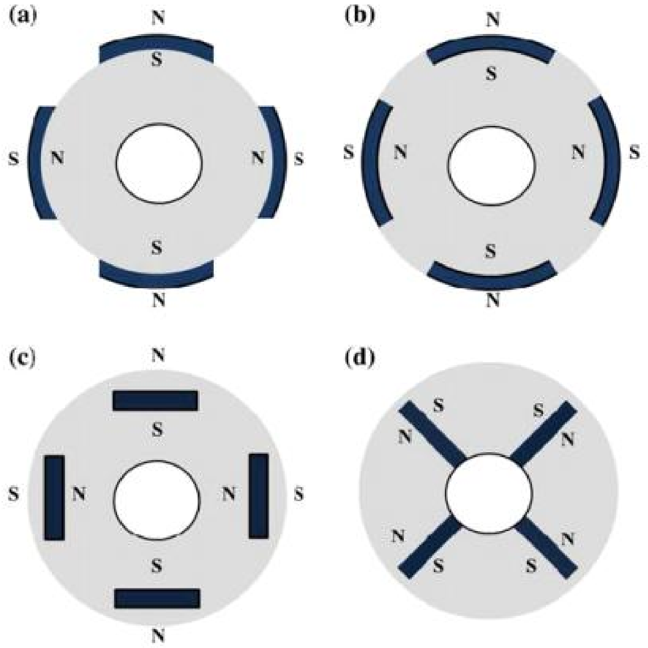


Fig.2.7 PMSM rotor permanent magnets layout:
a) surface PM, b) inset PM, c) interior PM, d) flux concentrating PM [40]

3. Interior magnets type: The magnets are integrated in the rotor's body (**Fig.2.7c**), the motor is a salient pole type. In this case, the rotor magnetism is anisotropic, the inductances depend on the rotor position. The magnets are placed on the rotor, providing more mechanical durability and robustness at high speeds. On the other hand, this motor is more expensive to manufacture and more complex to control.

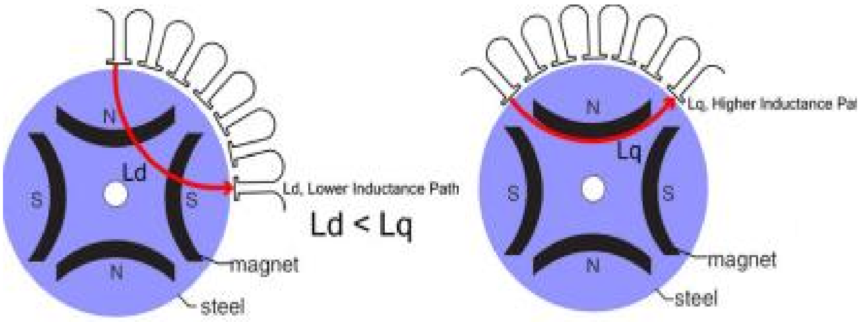
4. Flux concentrating type: As shown in **Fig.2.7d**, the magnets are deeply placed in the rotor's body. The magnets and their axes are radial. The flux on a polar arc of the rotor is a result of two separated magnets. The advantage of this configuration is the possibility to concentrate the flux generated by the permanent magnets in the rotor and to obtain a stronger induction in the gap. This type of machine has a salience effect. However, surface permanent magnet synchronous motors and interior permanent magnet synchronous motors are the most used in the industry.

Furthermore, the permanent magnet AC machines can be classified into two types: *trapezoidal* type called BLDC machines and *sinusoidal* type called PMSMs. The BLDCs operate with trapezoidal back electromagnetic force (EMF) and require rectangular stator phase current. The PMSMs generate sinusoidal EMF and operate with sinusoidal stator phase current. They are classified into two subcategories in terms of magnets position:

- **Salient Poles:** the magnets are buried into the rotor (**Fig.2.7c,d**). Interior Permanent Magnet Synchronous Motor (IPMSM). The direct axis reluctance is greater than the q-axis reluctance, because the effective air gap of the direct axis is multiple times that of the actual air gap seen by the q-axis. As consequence of such an unequal reluctance, the quadrature inductance is higher than direct inductance $L_q > L_d$. It produces reluctance torque in addition to the mutual torque (**Fig.2.8b**). Reluctance torque is produced due to the magnet saliency in the quadrature and the direct axis magnetic paths. Mutual torque is produced due to the interaction of the magnet field and the stator current. This arrangement of magnets is also much more robust mechanically as compared to surface-mounted machine. It makes possible to use IPMSM for higher-speed applications (contrary to SPMSM’s).

- **Non-salient Poles**: the magnets are located in the rotor surface (**Fig.2.7a**). They need special profiling to get a sinusoidal Back EMF (BEMF). This results in symmetrical air gap reluctance for the magnetic flux path. Such a motor is called a Surface-Mounted Permanent Magnet Synchronous Motor (SPMSM)**,** Machines with this arrangement of magnets are not preferred for high-speed applications (higher than 3000 rpm). The quadrature inductance is equal to the direct inductance $L_q = L_d$, Because of the same flux paths in d and q axis the reluctance torque disappears (**Fig.2.8a**).

Practically, even the surface-mounted PMSMs have slight asymmetry in their reluctance path due to manufacturing processes and materials used. A measure of this asymmetry is called, "saliency", which is calculated based on the inductance variation along the stator. Saliency produces its own torque, similar to a force produced on an iron bar in a solenoid. This torque is called "reluctance torque", which is different and additional to the ‘permanent magnetic torque’ that is produced due to interaction of stator and rotor fields.



a) IPMSM Inductances path

b) SPMSM Inductances path

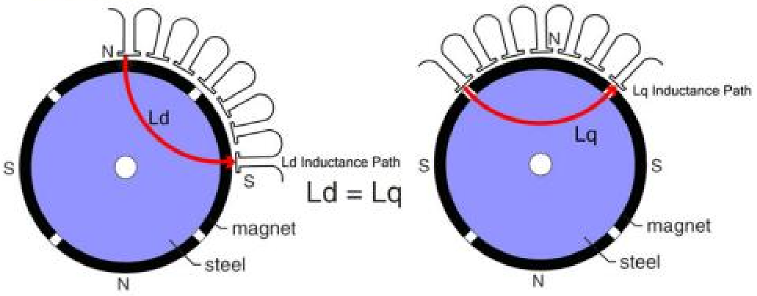


Fig.2.8 SPMSM versus IPMSM inductances path

2.3.5 Operating principle of PMSM

The permanent magnet synchronous motors are one of the types of AC synchronous motors, where the field is excited by permanent magnets that generate sinusoidal back EMF. It contains a rotor and a stator same as that of an induction motor, but a permanent magnet is used as a rotor to create a magnetic field. Hence there is no need to wound field winding on the rotor [46]. It is also known as a 3-phase brushless permanent sine wave motor.

The PMSM working principle is similar to the synchronous motor and it is very simple, fast, and effective when compared to conventional motors. The working of PMSM depends on the rotating magnetic field of the stator and the constant magnetic field of the rotor. The permanent magnets are used as a rotor to create constant magnetic flux, operates and locks at synchronous speed.

The phases are formed by joining the windings of the stator with one another. These phases are joined together to form different connections like a star, Delta, double and single phases. To reduce harmonic voltages, the windings should be wound shortly with each other.

When the 3-phase AC supply is given to the stator, it creates a rotating magnetic field and the constant magnetic field is induced due to the permanent magnet of the rotor. This rotor operates in synchronism with the synchronous speed. The whole working of the PMSM depends on the air gap between the stator and rotor with no load. If the air gap is large, then the windage losses of the motor will be reduced. The field poles created by the permanent magnet are salient. The permanent magnet synchronous motors are not self-starting motors. So, it is necessary to control the variable frequency of the stator electronically.

2.5 Mathematical model of PMSM

The study of an electric motor behavior is a hard task and requires good knowledge of its model to properly predict its dynamic behavior under different operating conditions.

In this section, the mathematical models of AC electric machines describing their electromechanical behaviors are established. The three-phase mathematical model of permanent magnet synchronous motors is developed. The classical models using the Concordia/Clarke and Park transformations are demonstrated in to define the two-phase equivalent models of AC machines. Using these transformations, many concepts, interpretations, and simplified models can be obtained to analyze the AC machine behavior. An approach to study AC machines is to transform the variables (voltages, currents, and flux linkages) stated in a fixed reference frame to a rotating frame defined by the Concordia/Clarke and Park transformations.

Modeling a permanent magnet synchronous motor is similar to a classical synchronous machine, except that the flux from the magnets is constant. Then, the model is derived from the classical synchronous machine [60]. To simplify the modeling of the machine, the following assumptions are introduced:

- The damping effect of the rotor is neglected.
- The magnetic circuit of the machine is not saturated.
- The distribution of the magneto-motive forces (MMF) is sinusoidal.
- The coupling capacitors between the windings are neglected.
- The hysteresis phenomena and the eddy currents are neglected.
- The gap irregularities owing to the stator slots are neglected.

Under these assumptions and using basic concepts, the electrical and mechanical equations describing the dynamical behavior of the PMSM are obtained.

2.5.1 Electric Equations

The three-phase stator voltage equations are expressed as:

$$\begin{aligned} V_{sa} &= R_s I_{sa} + \frac{d\Psi_{sa}}{dt} \\ V_{sb} &= R_s I_{sb} + \frac{d\Psi_{sb}}{dt} \\ V_{sb} &= R_s I_{sb} + \frac{d\Psi_{sc}}{dt} \end{aligned} \tag{2.1}$$

Or in a matrix form as:

$$[V_{sabc}] = R_s[I_{sabc}] + \frac{d[\Psi_{sabc}]}{dt} \tag{2.2}$$

Where:

$[V_{sabc}] = [v_{sa}, v_{sb}, v_{sc}]^T$ are the phase stator voltages.

R_s is the stator resistance.

$[I_{sabc}] = [i_{sa}, i_{sb}, i_{sc}]^T$ are the phase stator currents.

$[\Psi_{sabc}] = [\Psi_{sa}, \Psi_{sb}, \Psi_{sc}]^T$ are the stator fluxes.

2.5.2 Magnetic Equations

The stator flux is expressed as:

$$[\Psi_{sabc}] = [L_{ss}][I_{sabc}] + [\Psi_{rabc}] \tag{2.3}$$

Where $[\Psi_{rabc}]$ is the rotor (permanent magnet) flux which is given as:

$$\begin{bmatrix} \Psi_{ra} \\ \Psi_{rb} \\ \Psi_{rc} \end{bmatrix} = \Psi_r \begin{bmatrix} \cos(p\theta_m) \\ \cos(p\theta_m - \frac{2\pi}{3}) \\ \cos(p\theta_m + \frac{2\pi}{3}) \end{bmatrix} \tag{2.4}$$

θ_m is the rotor position angle, and *p* as the pole pair number.

The inductance matrix $[L_{ss}]$ as:

$$[L_{ss}] = \begin{bmatrix} L_{aa} & M_{ab} & M_{ac} \\ M_{ba} & L_{bb} & M_{bc} \\ M_{ca} & M_{cb} & L_{cc} \end{bmatrix} \tag{2.5}$$

where:

L_{aa}, L_{bb}, L_{cc} are the phases self-inductances.

M_{ab}, M_{ba}, M_{ac}, M_{ca}, M_{bc}, M_{cb} are the mutual inductances between phases.

For the salient pole machines, the inductance matrix $[L_{ss}]$ can be expressed as:

$$[L_{ss}] = [L_{so}] + [L_{sv}] \tag{2.6}$$

where:

$$[L_{so}] = \begin{bmatrix} L_{so} & M_{so} & M_{so} \\ M_{so} & L_{so} & M_{so} \\ M_{so} & M_{so} & L_{so} \end{bmatrix}$$

and:

$$[L_{sv}] = \begin{bmatrix} \cos(2p\theta_m) & \cos(2p\theta_m - \frac{2\pi}{3}) & \cos(2p\theta_m - \frac{2\pi}{3}) \\ \cos(2p\theta_m - \frac{2\pi}{3}) & \cos(2p\theta_m + \frac{2\pi}{3}) & \cos(2p\theta_m) \\ \cos(2p\theta_m + \frac{2\pi}{3}) & \cos(2p\theta_m) & \cos(2p\theta_m - \frac{2\pi}{3}) \end{bmatrix}$$

Then (2.2) becomes:

$$[V_{sabc}] = R_s[I_{sabc}] + \frac{d}{dt}\{[L_{ss}][I_{sabc}] + [\Psi_{sabc}]\} \tag{2.7}$$

Note that (2.7) is time varying and nonlinear.

2.5.3 The Concordia/Clark and Park Transformations

To derive an equivalent two-phase representation in order to facilitate the analysis and control design, the Park transformation is usually employed to obtain the expression of the model in the *(d, q)* frame. This transformation renders simpler the dynamical equations of the PMSM.

1. *Three-phase-Two-phase Transformation*: from an *(a, b, c)* three-phase stationary frame to an *(α, β)* two-phase stationary frame. This transformation is called the Concordia (obtained from Park transformation preserving energy) or Clarke transformation (obtained from Park transformation preserving amplitudes).
2. *Fixed frame-Rotating frame Transformation*: from an *(α, β)* two-phase stationary frame to a two-phase synchronous rotating *(d, q)* frame, this transformation is called the Park transformation.

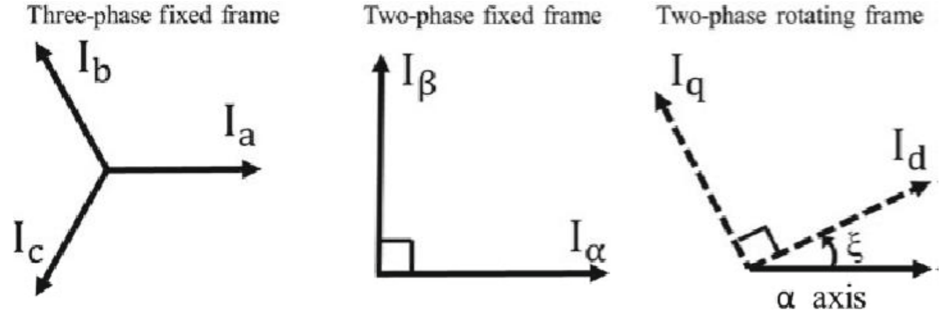


Fig.2.9 The Clark/Concordia-Park transformations

2.5.4 PMSM modeling in fixed two-phase frame

Now, an equivalent two-phase representation in a fixed frame is introduced. Using the Concordia transformation:

$$\begin{bmatrix} X_{s\alpha} \\ X_{s\beta} \end{bmatrix} = Co^T \begin{bmatrix} X_{s\alpha} \\ X_{s\beta} \\ X_{sc} \end{bmatrix} \tag{2.8}$$

Where:

$$C_0 = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{2.9}$$

multiplying by C_0 the left side of Eq. (2.7) and using the identity $C_0{}^T C_0 = I2\times 2$ with x a variable (voltage, current or flux), it follows that:

$$[V_{s\alpha\beta}] = R_s[I_{s\alpha\beta}] + \frac{d[\Lambda_{ss}]}{dt}[I_{s\alpha\beta}] + [\Lambda_{ss}]\frac{d[I_{s\alpha\beta}]}{dt} + \frac{d[\Psi_{r\alpha\beta}]}{dt} \qquad (2.10)$$

With: $[\Lambda_{ss}] = \{C_0{}^T[L_{ss}]C_0\}$.

Taking $M_{so} = -\frac{1}{2}L_{so}$ and using the following trigonometric equivalences:

$$\mathrm{Cos}\left(p\theta_m - \frac{2\pi}{3}\right) = \mathrm{Cos}(p\theta_m)\mathrm{Cos}\left(\frac{2\pi}{3}\right) + \mathrm{Sin}(p\theta_m)\mathrm{Sin}\left(\frac{2\pi}{3}\right)$$

$$\mathrm{Cos}\left(p\theta_m + \frac{2\pi}{3}\right) = \mathrm{Cos}(p\theta_m)\mathrm{Cos}\left(\frac{2\pi}{3}\right) - \mathrm{Sin}(p\theta_m)\mathrm{Sin}\left(\frac{2\pi}{3}\right)$$

Where: $\mathrm{Cos}\left(\frac{2\pi}{3}\right) = -\frac{1}{2}$ and $\mathrm{Sin}\left(\frac{2\pi}{3}\right) = \frac{\sqrt{3}}{2}$, it follows that:

$$[\Lambda_{ss}] = \frac{3}{2}L_{sv}\begin{bmatrix}\mathrm{Cos}(2p\theta_m) & \mathrm{Sin}(2p\theta_m)\\ \mathrm{Sin}(2p\theta_m) & \mathrm{Cos}(2p\theta_m)\end{bmatrix} + \frac{3}{2}L_{so}\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} = \begin{bmatrix}L_\alpha & L_{\alpha\beta}\\ L_{\alpha\beta} & L_\beta\end{bmatrix} \qquad (2.11)$$

whose the time derivative is given by:

$$\frac{d[\Lambda_{ss}]}{dt} = L_{sv}p\Omega\begin{bmatrix}-\mathrm{Sin}(2p\theta_m) & \mathrm{Cos}(2p\theta_m)\\ \mathrm{Cos}(2p\theta_m) & \mathrm{Sin}(2p\theta_m)\end{bmatrix} \qquad (2.12)$$

Furthermore, using the Concordia transformation, the fluxes $\Psi_{r\alpha}$ and $\Psi_{r\beta}$ can be expressed as:

$$\begin{bmatrix}\Psi_{r\alpha}\\ \Psi_{r\beta}\end{bmatrix} = Co^T\begin{bmatrix}\Psi_{ra}\\ \Psi_{rb}\\ \Psi_{rc}\end{bmatrix} \qquad (2.13)$$

$$= \sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\Psi_r\begin{bmatrix}\mathrm{Cos}(p\theta_m)\\ \mathrm{Cos}(p\theta_m - \frac{2\pi}{3})\\ \mathrm{Cos}(p\theta_m + \frac{2\pi}{3})\end{bmatrix} \qquad (2.14)$$

It follows that:

$$\begin{bmatrix}\Psi_{r\alpha}\\ \Psi_{r\beta}\end{bmatrix} = \sqrt{\frac{3}{2}}\Psi_r\begin{bmatrix}\mathrm{Cos}(p\theta_m)\\ \mathrm{Sin}(p\theta_m)\end{bmatrix} \qquad (2.15)$$

Where: $\mathcal{J} = \begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix}$ is a skew-symmetric matrix, satisfying the following property:

$$\mathcal{J}^T\mathcal{J} = I$$

The time derivative of (2.15) is of the form:

$$\begin{bmatrix}\frac{d\Psi_{r\alpha}}{dt}\\ \frac{d\Psi_{r\beta}}{dt}\end{bmatrix} = \begin{bmatrix}-p\Omega\Psi_{r\beta}\\ p\Omega\Psi_{r\alpha}\end{bmatrix} \qquad (2.16)$$

2.5.5 PMSM modeling in rotating two-phase frame

An equivalent two-phase representation in a rotating frame is introduced. Using the overall Park transformation, the electric equations of a three-phase model (stationary abc frame) of the motor are transformed into the two-phase model (rotatory *(d, q,* 0*)* frame). The *(d, q,* 0*)* transformation can reduce three AC variables (voltages, currents…) to two DC variables or by applying the first transformation, i.e., the Concordia transformation Co, then the second step is the application of the park transformation P in order to obtain the two-phase synchronous rotating representation of the PMSM.

The resulting voltage equations are given as:

$$\begin{bmatrix} x_{sd} \\ x_{sq} \end{bmatrix} = P(\theta_e)^T \begin{bmatrix} x_{s\alpha} \\ x_{s\beta} \end{bmatrix} \tag{2.17}$$

Where:

$$\mathrm{P}(\theta_{\mathrm{e}}) = \begin{bmatrix} \mathrm{Cos}\theta_{\mathrm{e}} & -\mathrm{Sin}\theta_{\mathrm{e}} \\ \mathrm{Sin}\theta_{\mathrm{e}} & \mathrm{Cos}\theta_{\mathrm{e}} \end{bmatrix}$$

$\theta_{\mathrm{e}} = \mathrm{p}\theta_{\mathrm{m}}$ is the electrical angle defined from the position of the rotor with respect to stator. Then,

$$\begin{bmatrix} x_{sd} \\ x_{sq} \end{bmatrix} = P(\theta_e)^T \begin{bmatrix} x_{s\alpha} \\ x_{s\beta} \end{bmatrix} = P(\theta_e)^T Co^T \begin{bmatrix} x_{sa} \\ x_{sb} \\ x_{sc} \end{bmatrix} \tag{2.18}$$

Combining Eq. (2.18) with (2.7), it follows that:

$$CoP(\theta_e)P(\theta_e)^T Co^T[V_{sabc}] =$$

$$R_s CoP(\theta_e)P(\theta_e)^T Co^T[I_{sabc}] + \frac{d}{dt}\{[\Psi_{rabc}]\} + \frac{d}{dt}\{[L_{ss}]CoP(\theta_e)P(\theta_e)^T Co^T[I_{sabc}]\} \tag{2.19}$$

Then the model of the PMSM in the *(d, q)* frame is obtained:

$$[V_{sdq}] = R_s[I_{sdq}] + P(\theta_e)^T \frac{d}{dt}\{[\Lambda_{ss}]P(\theta_e)\}[I_{sdq}] + P(\theta_e)^T[\Lambda_{ss}]P(\theta_e)\frac{d}{dt}\{[I_{sdq}]\} - p\Omega\,\mathcal{J}[\Psi_{rdq}] \tag{2.20}$$

In case of IPMSM, the voltage equation is given as:

$$[V_{sdq}] = \{[R_s] - p\Omega[L_{dq}]\mathcal{J}\}[I_{sdq}] + [L_{dq}]\frac{d[I_{sdq}]}{dt} - p\Omega\,\mathcal{J}[\Psi_{rdq}] \tag{2.21}$$

Moreover, for a specific value of θ_e, the q-component of the rotor flux equal to zero (i.e., Ψ_{rq}) and the d-component of the rotor flux equal to Ψ_{r}, ($\Psi_{\mathrm{rd}} = \Psi_{\mathrm{r}}$) , it follows that:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} R_s & -p\Omega L_q \\ p\Omega L_d & R_s \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} \frac{di_{sd}}{dt} \\ \frac{di_{sq}}{dt} \end{bmatrix} - \begin{bmatrix} 0 \\ p\Omega\Psi_r \end{bmatrix} \tag{2.22}$$

2.5.6 Mechanical Equations

The rotor electrical position θ_e is determined by:

$$\frac{d\theta_e}{dt} = \omega \tag{2.23}$$

And the rotor speed Ω from:

$$J\frac{d\Omega}{dt} = f_v\Omega = T_e - T_l \tag{2.24}$$

Where:

ω = p*Ω: the angular electrical speed.

p: the pole pairs number.
Ω: the rotor angular speed.

T_e: the electromagnetic torque.

T_l: the load torque.

J: the inertia moment. i.e., the inertia of the synchronous machine plus the load inertia.

f_v: the viscous friction coefficient.

The electromagnetic torque T_e is generated by the interaction between the rotor magnets poles and the poles induced by the magneto-motive forces in the air gap.
Then, the electromagnetic torque T_e is given in case of IPMSM as [3]:

$$T_e = p(L_d - L_q)i_{sd}i_{sq} + p[\Psi_{rd}i_{sq} - \Psi_{rq}i_{sd}] \tag{2.25}$$

By replacing (2.25) in (2.24), then:

$$J\frac{d\Omega}{dt} + f_v\Omega = p(L_d - L_q)i_{sd}i_{sq} + p[\Psi_{rd}i_{sq} - \Psi_{rq}i_{sd}] - T_l \tag{2.26}$$

Choosing the orientation of the (d, q) frame such that the q-component of the rotor flux is equal to zero ($\Psi_{rq} = 0$) and the d-component of the rotor flux is equal to Ψ_r, then (2.26) can be expressed as:

$$J\frac{d\Omega}{dt} + \Omega = p(L_d - L_q)i_{sd}i_{sq} + p[\Psi_r i_{sq}] - T_l \tag{2.27}$$

The final model of the IPMSM, in the rotor flux oriented (d, q) frame is:

$$\begin{gathered}
\frac{di_{sd}}{dt} = -\frac{R_s}{L_d}i_{sd} - p\Omega\frac{L_q}{L_d}i_{sq} + \frac{v_{sd}}{L_d} \\
\frac{di_{sq}}{dt} = -\frac{R_s}{L_d}i_{sq} - p\Omega\frac{L_d}{L_q}i_{sd} + \frac{v_{sq}}{L_q} - p\Omega\frac{\Psi_r}{L_q} \\
\frac{d\Omega}{dt} = -\frac{f_v}{J}\Omega + \frac{1}{J}p(L_d - L_q)i_{sd}i_{sq} + p\Psi_r i_{sq} - \frac{1}{J}T_l
\end{gathered} \tag{2.28}$$

For the SPMSM, ($L_d = L_q = L_s$). Then, the electromagnetic torque is only given as:

$$T_e = p\Psi_r i_{sq} \tag{2.29}$$

Replacing (2.29) in (2.24) with $L_d = L_q = L_s$, it follows that the rotor speed dynamics is given as:

$$J\frac{d\Omega}{dt} = -f_v\Omega + p\Psi_r i_{sq} - T_l \tag{2.30}$$

Then the final SPMSM model in the rotor flux oriented (d,q) frame is:

$$\frac{di_{sd}}{dt} = -\frac{R_s}{L_s}i_{sd} + p\Omega i_{sd} - \frac{v_{sd}}{L_s} \tag{2.31}$$

$$\frac{di_{sq}}{dt} = -\frac{R_s}{L_s}i_{sq} - p\Omega i_{sd} + \frac{v_{sq}}{L_s} - p\Omega\frac{\Psi_r}{L_s} \tag{2.32}$$

$$\frac{d\Omega}{dt} = -\frac{f_v}{J}\Omega + \frac{p\Psi_r}{J} - \frac{1}{J}T_l$$

2.5.7 State-space model of PMSM

For the torque or angular speed control, the nonlinear state-space model of the IPMSM in the *(d, q)* frame is shown in (2.33). However for the SPMSM: $(L_d = L_q = L_s)$.

$$\begin{bmatrix}\frac{di_{sd}}{dt}\\ \frac{di_{sq}}{dt}\\ \frac{d\Omega}{dt}\end{bmatrix} = \begin{bmatrix}-\frac{R_s}{L_s}i_{sd} + \frac{pL_q}{L_d}i_{sq}\Omega\\ -\frac{R_s}{L_q}i_{sq} + \frac{pL_d}{L_d}i_{sd}\Omega - \frac{p\Psi_r}{L_q}\Omega\\ \frac{p\Psi_r}{J}i_{sq} - \frac{p(L_q-L_d)}{L_q}i_{sd}i_{sq} - \frac{f_v}{J}\Omega\end{bmatrix} + \begin{bmatrix}\frac{1}{L_d} & 0 & 0\\ 0 & \frac{1}{L_q} & 0\\ 0 & 0 & -\frac{1}{J}\end{bmatrix}\begin{bmatrix}v_{sd}\\ v_{sq}\\ T_l\end{bmatrix} \tag{2.33}$$

where:

$[i_{sd}, i_{sq}\ , \Omega]$ are the states.

$[v_{sd}, v_{sq}, T_l\ ]$ are the inputs, where T_l is assumed to be an unknown input.

The measurable outputs are the stator currents $[i_{sd}, i_{sq}]$.

2.6 Control techniques of PMSM

The basic block scheme of adjustable speed drive with control block for PMSM is presented in **Fig.2.10**. It consists of two parts: power and control part employed microprocessor.

The main requirements for high performance PWM inverter-fed PMSM drive are: Operation with and without mechanical motion sensor, fast flux and torque response, available maximum output torque in wide range of speed operation region, constant switching frequency, low flux and torque ripples, robustness to parameters variation, four quadrant operation. To meet the above requirements, different control methods can be used [5].

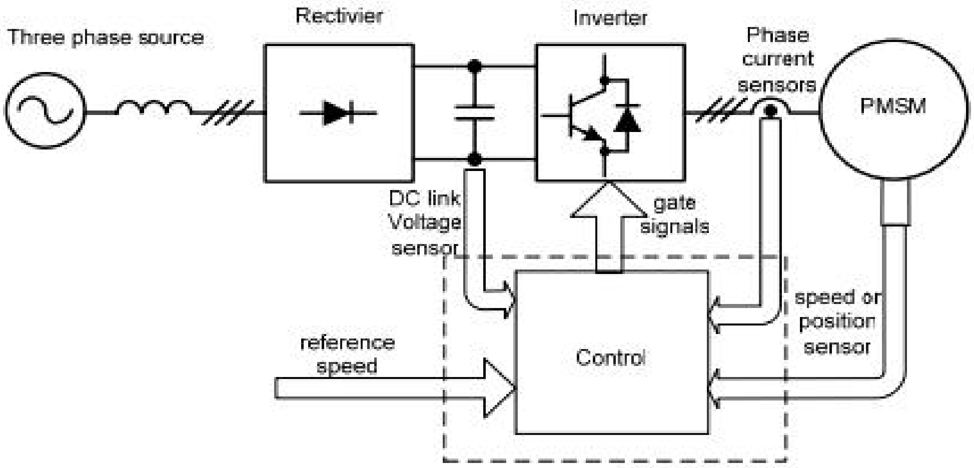


Fig.2.10 The basic block scheme of PMSM drive supplied voltage source inverter [61]

The main task of control block is to follow demand reference speed by motor and provide proper operation in static (insight of the limits) and dynamic states without any instability. This is ensured through suitable generated gate signals for the IGBT transistor inside of the inverter. Therefore, to make good decision how to control power transistors in the inverter, the following feedback signals are measured and used:

- motor phase currents
- speed or position of the rotor
- DC link voltage

This significantly improves dynamic behavior of the system (good performance of the torque and speed response, very fast dynamics response with fully controllable torque in wide speed range).

The general classification of the variable frequency control methods for PMSM is presented in **Fig.2.11**, the PMSM control methods can be divided into *scalar* and *vector control*. In scalar control, which based on a relation valid for steady states, only the magnitude and frequency (angular speed) of voltage, currents, and flux linkage space vectors are controlled. Thus, the control system does not act on space vector position during transient times. Therefore, this control is dedicated for application, where high dynamics is not demanded [6]. Another problem with scalar control is that the motor flux and torque in general are coupled [62]. This inherent coupling affects the response and makes the system prone to instability if it is not considered.

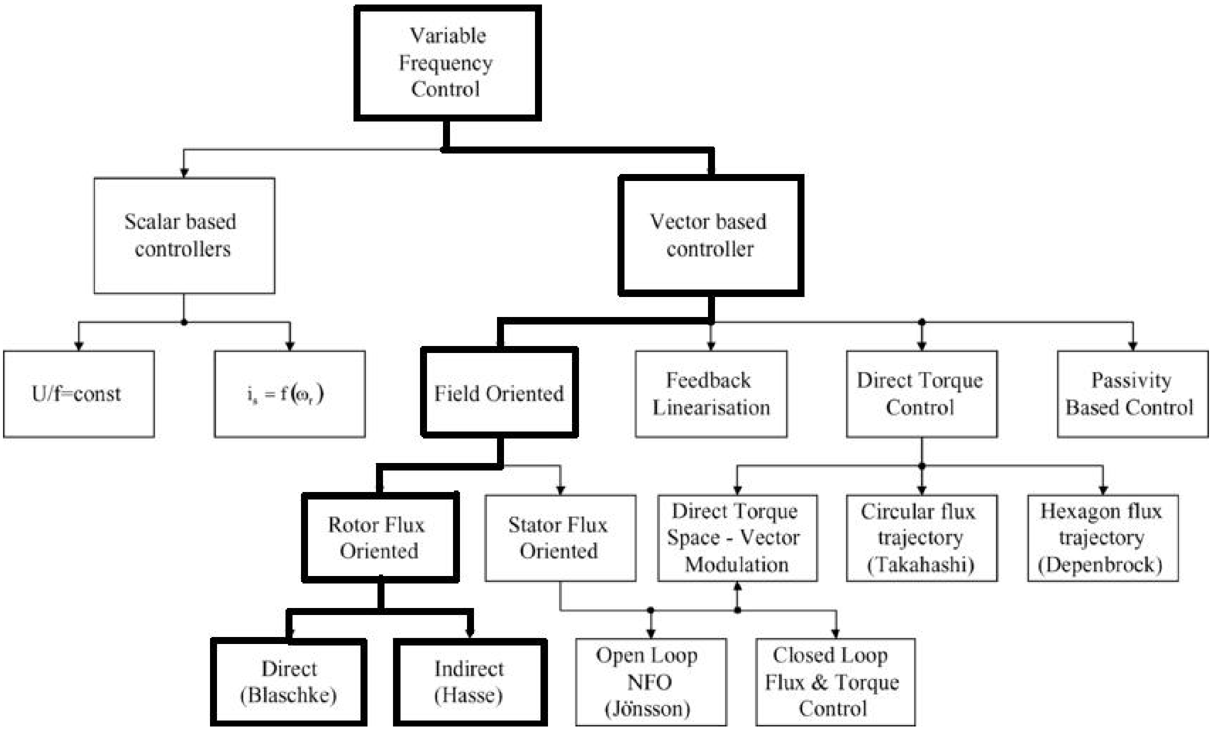


Fig.2.11 Classification of PMSM control methods [61]

One control technique in the scalar control is known as V/F control where the motor is controlled by adjustable stator voltage magnitude and frequency in such a way that the air gap flux is always maintained at desired value under steady state.

On the contrary, the vector control which is based on relation valid for dynamics states, not just magnitude and frequency (angular speed), but also instantaneous position of voltage, current and flux space vectors are controlled. Thus, the control system adjusts the position of the space vectors and guarantees their correct orientation for both steady states and transients.

2.6.1 Direct torque control of PMSM

Direct Torque Control was first introduced for induction motors [9] in 1984 in Japan Takahashi and Nagochi and also in Germany by Depenbrock under the name of Direct Self-Control (DSC) [10] in 1985. The methods were characterized by their simplicity, good performance and robustness. Unlike the FOC method, DTC worked without any external measurement of the rotors mechanical position. The reason behind the simplicity is that DTC not require any current regulators, transformations to rotating reference frame or PWM generators. Direct torque control achieves a decoupled control of the stator flux and the electromagnetic torque in the stationary frame (α, β). It uses a switching table for the selection of an appropriate voltage vector. The selection of the switching states is related directly to the variation of the stator flux and the torque of the machine. Hence, the selection is made by restricting the flux and torque magnitudes within two hysteresis bands. Those controllers ensure a separated regulation of both of these quantities. The inputs of hysteresis controllers are the flux and the torque errors as well as their outputs determine the appropriate voltage vector for each commutation period.

2.6.2 Field oriented control of PMSM

During many years a DC motor has been mostly used. Because of simple control method, which based on fact that flux and torque can be controlled separately using current control loop with PI controllers. However the weak point of this drive was DC motor, which could not worked in aggressive or volatile environment and required cyclical maintenance. This disadvantages has been eliminated, when instead of DC machine a three phase PMSM motor were used. In searching new control method for induction machine in 1972 was developed vector control method known as field oriented control (FOC) [7,8]. This method allows control the flux and the torque in the AC machine in similar way as for DC motor. It was achieved by transform current vector in stationary reference frame (α,β) into new coordinate system (d,q) with respect to rotor (magnet) flux vector. So the flux produced by permanent magnet is frozen to the direct axis of the rotor (see **Fig.2.12**).

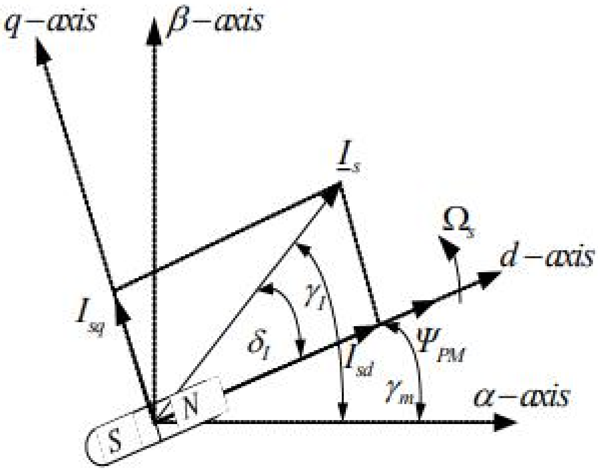


Fig.2.12 Vector diagram illustrated the principle of FOC [61]

Further, stator current vector can be split into two current components: flux current is_d and torque producing current is_q. In analogy to separate commutator motor, the flux current components corresponds to excitation current and torque-producing current corresponds to the armature current.

The main question is how or in which manner produce the reference currents components $is_{d\ ref}$, $is_{q\ ref}$ in respect to requirement of references torque, speed and flux. Its leads to many realization of current control structure. Among them generally we can distinguish two structures of current control loop. One of them is hysteresis based control (**Fig.2.13**) [65] and the second one is PI based current controllers without an outer speed control (**Fig.2.14**).

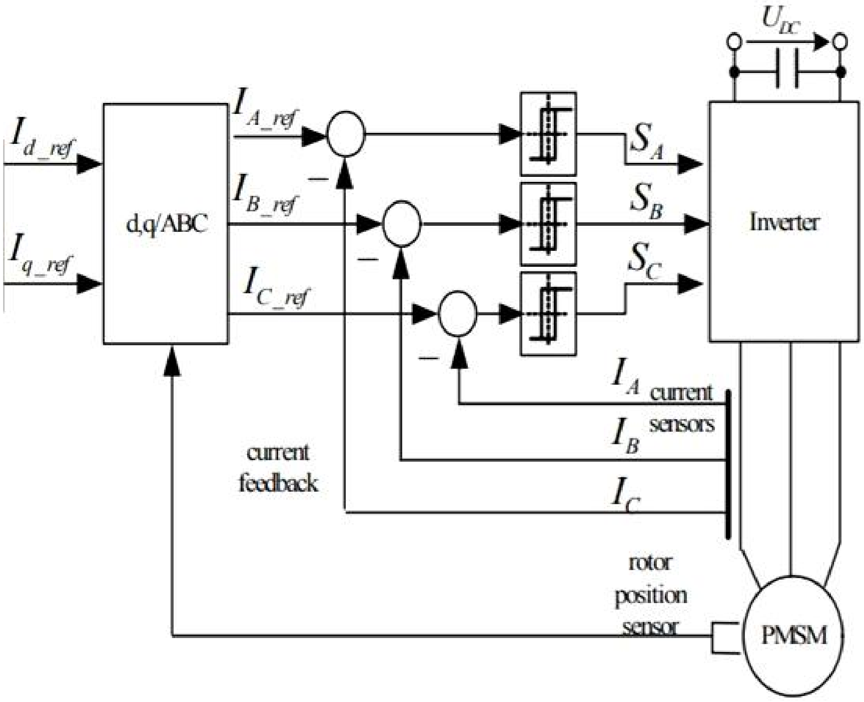


Fig.2.13 Vector control structure for PMSM with: hysteresis based controllers [61]

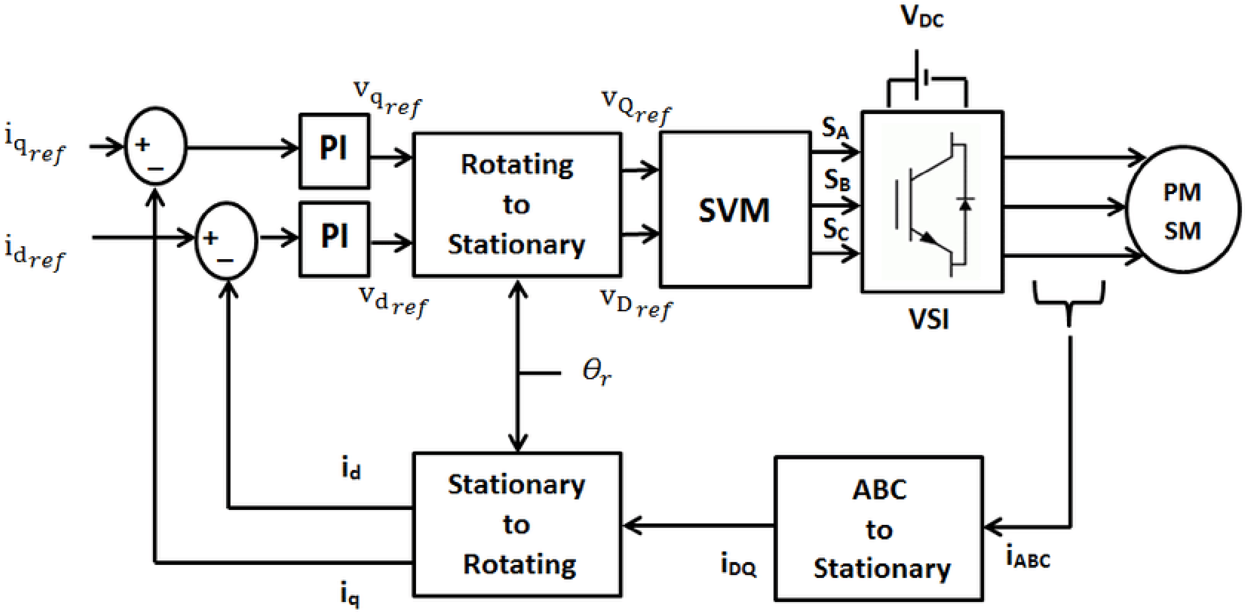


Fig.2.14 Vector control structure for PMSM with: PI current controllers [61]

Hysteresis based current control has following disadvantage such as [65]:

- Measurement of three phase currents is required.
- Three independent hysteresis current controllers are required.
- Variable switching frequency is achieved with fast sampling time is required.

All this listed above disadvantage can be eliminate, when the PI current controllers are used, this structure is mostly used in industrial application, an outer speed PI controller can be added in the outer control loop as in **Fig.2.15**.

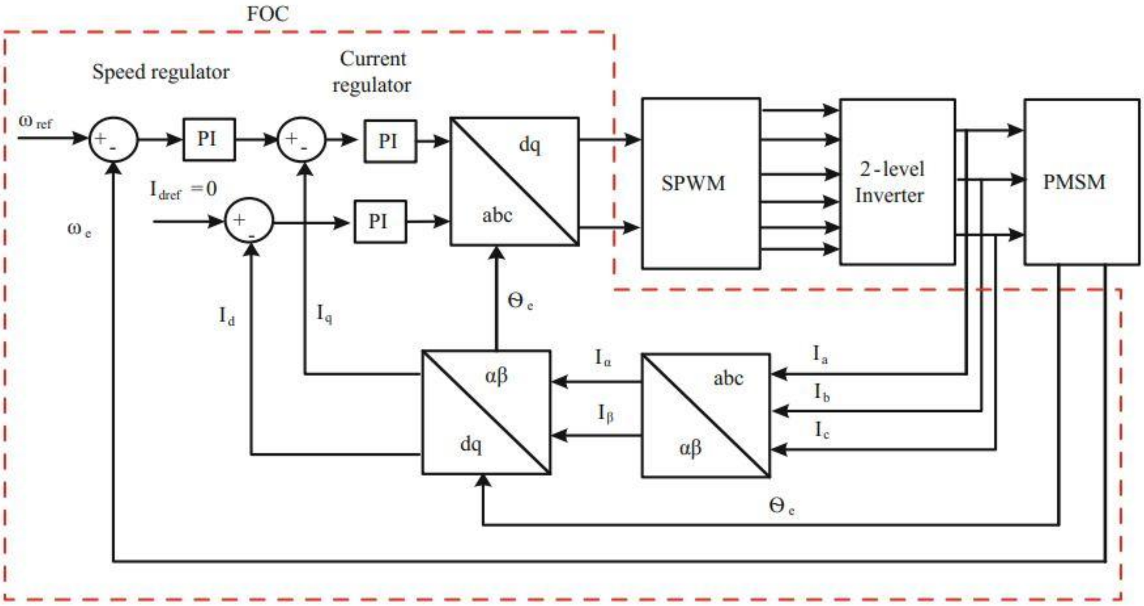


Fig.2.15 Vector control structure for PMSM with: PI current and speed controllers [66]

From eq(2.33) and eq(2.25) by taking the $[i_{sd}, i_{sq}]$ as the states and for the case of non-salient poles permanent magnet synchronous machine (SPMSM) and from eq(2.29):

$$i_{sqref} = \frac{T_{eref}}{p\Psi_r} \tag{2.34}$$

For many years the CTA control (i_{sdref} =0) method has been a popular technique for a long time because of simple control. This method was dedicated for surface permanent magnet synchronous motor (SPMSM), where the magnetic saliency does not exist [61]. So the maximum torque per ampere is obtained, when stator current vector is shifted in respect to rotor flux vector 90 degree. However, in IPMSM, maximum torque per ampere is obtained with torque angle more than 90 degree. This is because of existence of reluctance torque component due to magnetic saliency. Therefore, the i_{sdref} should be negative value [61].

The block diagram of field oriented control (FOC) of PMSM in **Fig.2.15** which has the decoupled torque and flux channels with feedback. The rotor position information is required for the FOC of the motor. Motor speed is compared with reference speed and the error is fed as input to the PI controller whose output will be proportional to torque producing component of stator current (i_{sqref}). This current is compared with q-axis component of stator current (i_{sq}) and error is fed to another PI controller to find q-axis reference voltage component V_{qref}. The d-axis component of stator reference current which is the flux producing component (i_{sdref}) is taken equal to zero to satisfy maximum torque per ampere condition. This current is compared with motor d-axis current component and the error is fed to PI controller to find V_{dref}.

The reference voltage vector is generated by different operating times of null vector and adjacent vectors in the sector in which V_{ref} lies (to be more detailed in the following section). For a sampling period T_s, the operating time of active vectors and null vectors should satisfy the volt sec balance without forgetting that the V_{qref} and V_{dref} components of voltage is transformed into V_{aref} and $V_{\beta ref}$ before fed as input to SVPWM block

2.7 Voltage source inverter for PMSM supply

As shown in the **Fig.2.10**, the adjustable speed drive (ASD) commonly used in industrial applications to supply three-phase AC motor consists of a diode rectifier, DC link filter and an inverter. The rectifier converts supply AC voltage into DC voltage. The DC voltage is filtered by a capacitor in the DC link. The inverter converts the DC to a variable voltage, variable frequency AC for motor speed or (torque/current) control.

The constant DC voltage made by the rectifier is delivered the to the input of the inverter which thanks to the controlled transistor switches, converts this voltage to a three-phase AC voltage signal with wide range variable voltage amplitude and frequency. One leg of the inverter consists of two transistor switches as in **Fig.2.16**. A simple transistor switch consists of a feedback diode connected in anti-parallel with a transistor. The feedback diode conducts current when the load current direction is opposite to the voltage direction.

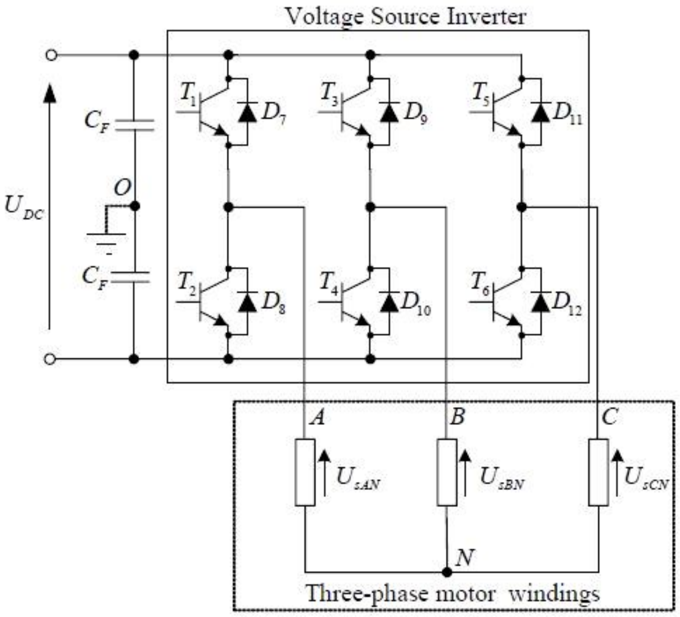


Fig 2.16 Basic scheme of voltage source inverter circuit [61]

Assuming that the power devices are ideal, when they are conducting, the voltage across them is zero and they present an open circuit in their blocking mode. Therefore, each inverter leg can be represented as an ideal switch. It gives possibility to connect each of the three motor phase coils to a positive or negative voltage of the dc link. Thus, the equivalent scheme for the three-phase inverter and possible eight combinations of the switches in the inverter are shown in **appendix B**.

The inverter's control bases on the logic values Si, where:

$S_i = 1$, T_i is ON and $\overline{T_i}$ is OFF.

$S_i = 0$, T_i is ON and $\overline{T_i}$ is ON.

With: $i = a, b, c$.

The voltage vector is generated by the following equation

$$V_s = \sqrt{\frac{3}{2}} V_{dc} \left[S_a + S_b e^{j\frac{2\pi}{3}} + S_c e^{j\frac{4\pi}{3}} \right] \tag{2.43}$$

V_{dc}: DC link voltage.

There are eight possible positions from the combinations of the switching states. Six are active (basic) vectors (V1, V2 … V6) and two are zero (null) vectors (V0, V7).

2.7.1 Space vector pulse width modulation

Space Vector Pulse Width Modulation (SVPWM) is a technique used in the final step of field oriented control (FOC) to determine the pulse-width modulated signals for the inverter switches in order to generate the desired 3-phase voltages to the motor. SVPWM is claimed to be more efficient compared to natural and regular sampled PWM.

The principle of SVM is the prediction of inverter voltage vector by the projection of the reference vector V_s* between adjacent vectors corresponding to two non-zero switching states. For a two-level inverter, the switching vectors diagram forms a hexagon divided into six sectors, each one is expanded by 60° as shown in **Fig.2.17**.

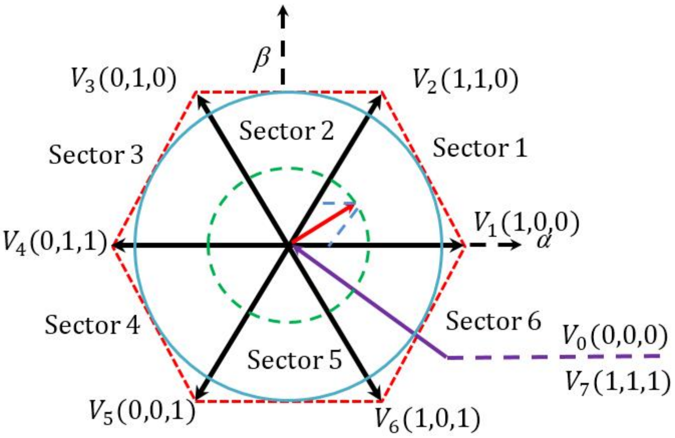


Fig 2.17 Representation of the inverter states in the complex space [61]

The application time for each vector can be obtained by vector calculations and the rest of the time period will be spent by applying the null vector.

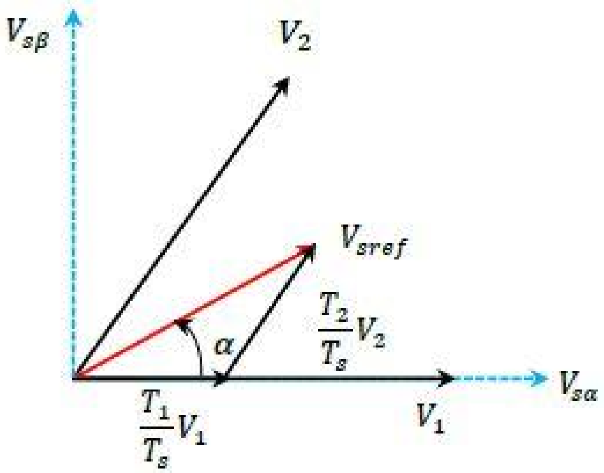


Fig 2.18 Reference vector as a combination of adjacent vectors at sector 1 [61]

In each sector, the basic vectors associated with that sector are firstly found, and then the synthesizing of the reference vector is done by switching between the two vectors (In this case V_1 and V_2).

The volt-second principle for sector 1 can be expressed by:

$$V_{sref}T_s = V_1T_1 + V_2T_2 + V_0T_0 \tag{2.44}$$

$$T_s = T_1 + T_2 + T_0 \tag{2.45}$$

Where:

T_1, T_2, T_0 are the corresponding application times of the voltage vectors respectively.

T_s is the sampling time.

The determination of times T_1 and T_2 corresponding to the voltage vectors are obtained by simple projections.

$$\begin{cases} T_1 = \frac{T\sqrt{3}}{\sqrt{3}V_{dc}}\left(V_{\alpha ref} - \frac{V_{\beta ref}}{\sqrt{3}}\right) \\ T_2 = \sqrt{2}\frac{T}{V_{dc}}V_{\beta ref} \end{cases} \tag{2.46}$$

V_{dc}: DC bus voltage.

The calculation of the switching times (duty cycles) is expressed as follows:

Upper side:

$$T_{aon} = T_1 + T_2 + \frac{T_0}{2} \tag{2.47}$$

$$T_{bon} = T_2 + \frac{T_0}{2} \tag{2.48}$$

$$T_{bon} = \frac{T_0}{2} \tag{2.49}$$

Lower side:

$$T^*{}_{aon} = \frac{T_0}{2} \tag{2.50}$$

$$T^*{}_{bon} = T_1 + \frac{T_0}{2} \tag{2.51}$$

$$T^*{}_{con} = T_1 + T_2 + \frac{T_0}{2} \tag{2.52}$$

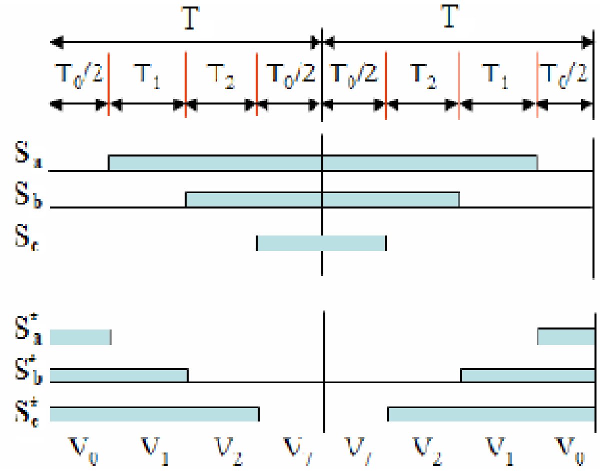


Fig 2.19 Switching times for sector 1 [61]

Switching times for other sectors are to be shown in the **appendix B**.

2.8 Simulation of field oriented control with space vector modulation (FOC-SVM)

This section presents the simulation of field oriented control with space vector modulation of SPMSM. It has been implemented in Simulink, this software provides an interactive graphical environment and set of block libraries that let you simulate a variety of time-varying systems.

2.8.1 Simulation description

The mathematical equations discussed previously have been modeled using Simulink. The simulation covered both the starting up and the steady states operation of the controlled motor without/with load. The simulation has been conducted in a time of 0.4seconds for three phase non-salient pole rotor 415W SPMSM with characteristics given in the **appendix B**.

Load torque of 2.5N.m (Full-load) was applied at t=0.2sec, Furthermore, the rotor speed response is compared to a speed reference of 1000 rpm.

Fig.2.20 presents the Simulink block of FOC-SVM of SPMSM.

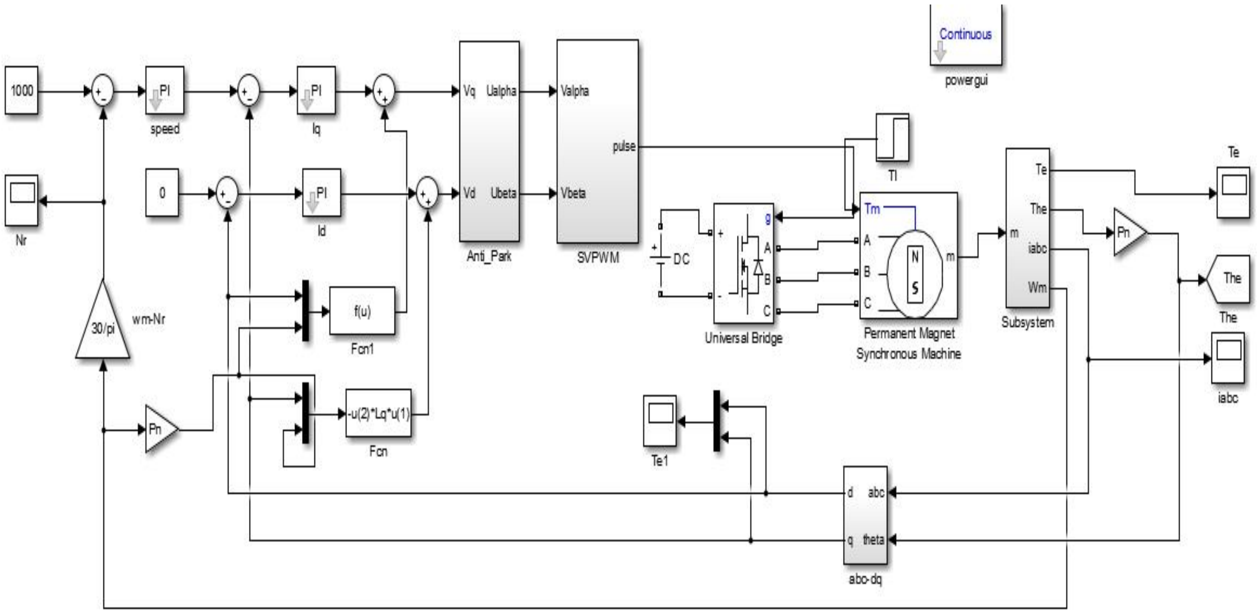


Fig.2.20 Simulink block of FOC-SVM of SPMSM

Some interior blocks are obtained from the simulink library directly and some are built based on their mathematical models seen previously.

2.8.2 Simulation results analysis

The following figures represent the results of simulation of field oriented control based on space vector modulation of SPMSM.

- **Rotor speed response analysis**

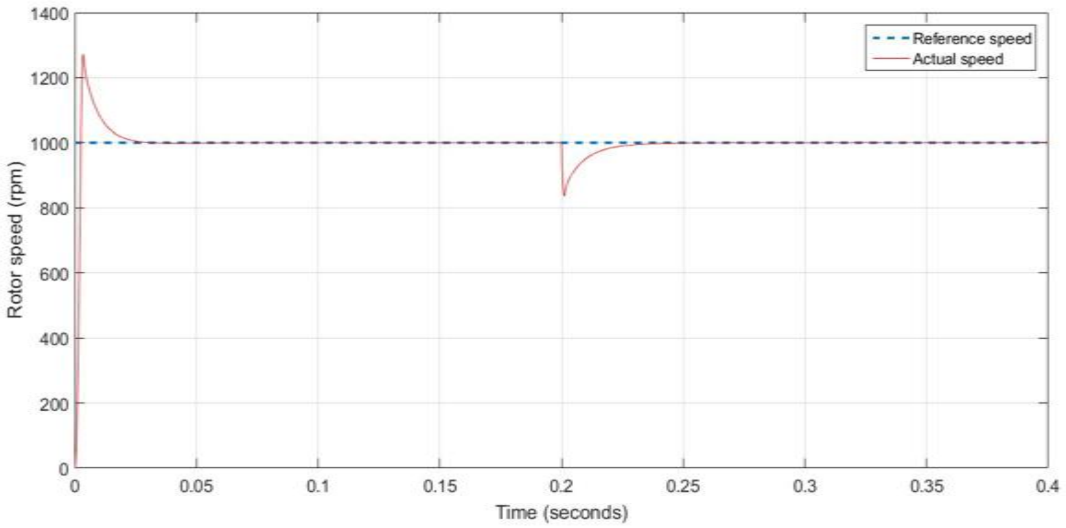


Fig.2.21 Rotor speed response

When starting (No-load condition), the speed signal stabilizes after a short response time of 0.02sec, then the speed of rotation signal follows the reference speed (1000rpm).

When load torque was applied at t=0.2sec, speed of the motor decreases for a time of 0.02sec then re-follows the reference speed. This is known for Torque-speed relationship, they are said to be inversely proportional (ability to generate torque diminishes with increase of speed) and the reason for this is because the back EMF opposes the supply that is attempting to force current into the stator, that will generate EM-Torque.

- **Stator currents analysis**

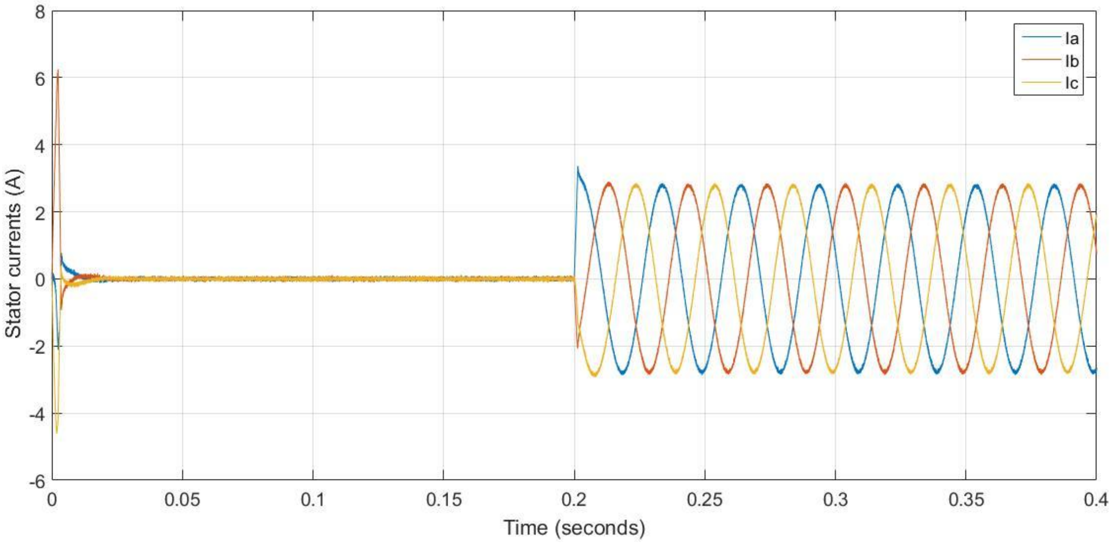


Fig.2.22 Stator currents in abc frame

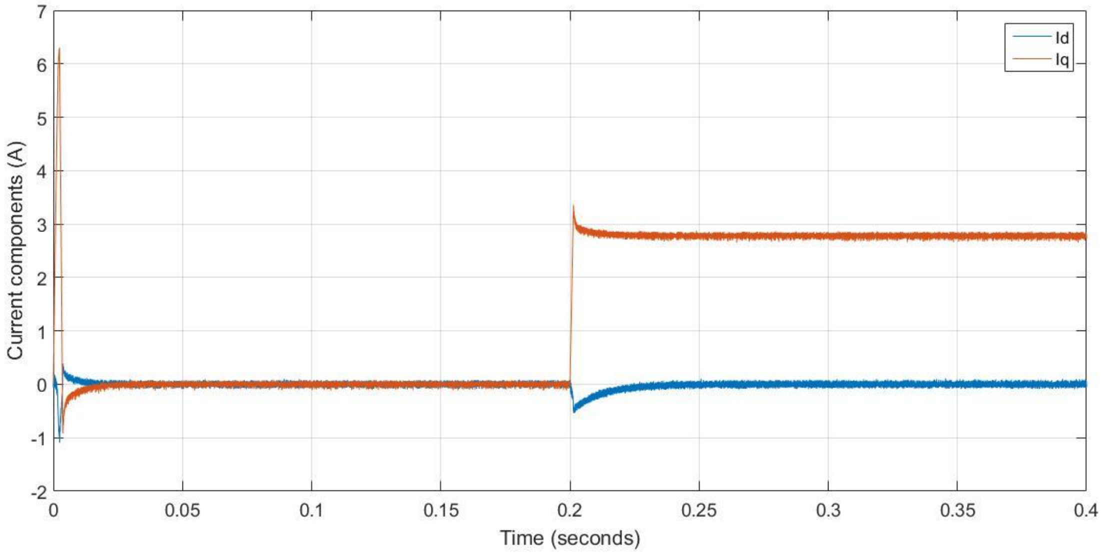


Fig.2.23 Stator currents in d-q frame

In the three phase abc frame, low oscillations observed in stator currents signals for a short duration of 0.02sec then stabilizes around zero when no loaded. When load torque application at t=0.2sec, stator currents are periodic sinusoids with magnitude of 2.8A and shifted 120° apart.

In the two phase rotary d-q frame, the direct stator current is oscillating around zero with a small undershoot having a short duration of 0.02sec. This direct stator current is efficient and sufficient to achieve the MTPA when applying the CTA control command in the field oriented control of SPMSMs. Whereas the quadratic stator current which is the torque producing current is matching the torque as in **Fig.2.24** to provide the required torque on the motor shaft.

- **Torque response analysis**

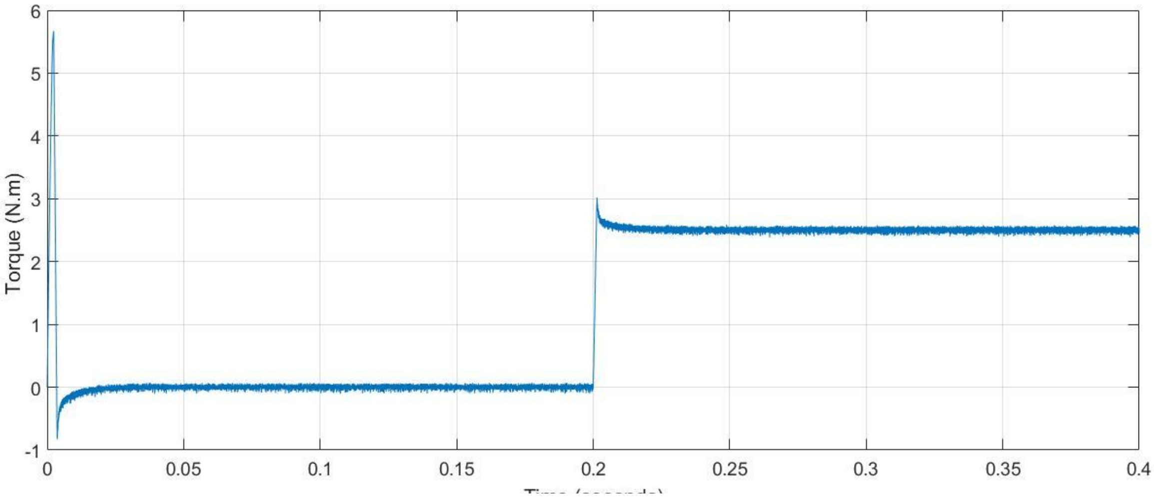


Fig.2.24 Torque response

Torque produced by the motor reaches its maximum value (5.7N.m) then disappears once the steady state is reached. When load torque is applied, the torque increases to instantly compensate for the load torque then decreases to match the full load torque (2.5N.m) with a few additional ripples caused by the inverter (but always less enough comparing to FOC or other control methods in case where the inverter is not fed by the PWM or SVPWM).

2.8.3 Simulation results conclusion

A summary to be created about the results of this simulation is that vector control technique (FOC-SVM) with PI controllers (in the outer and inner loops) for a permanent magnet synchronous motor is a good and efficient control technique to be used. The PI controllers had a good dynamic response where the steady states commands were attained. This control method would be reliable on when the need of good ability to reject perturbations and ripples elimination.

Since this thesis is about fault tolerant control, one thing can be noticed is that the results of this simulation represent the healthy state response to the motor parameters and to the control commands. Those results are the image of a healthy electric drive system and are sufficient to be set as a reference when compared to the results of an electric drive system under fault events which is the work to be done in the next chapter.

2.9 Chapter conclusion

In this chapter, Permanent magnet synchronous motor (PMSM) was discussed, starting with its advantages and applications comparing with other motors, then its construction and operating principle. Models were then presented to describe the dynamic behavior of the machine. These models were expressed through mathematical modeling based on various simplifying assumptions and general park model. Finally, we presented the vector control strategy with the space vector modulation (FOC-SVM) aiming for a speed variation of the SPMSM, associated with a simulation in Simulink software where the results were satisfying.

The control strategy used (FOC-SVM) requires accurate knowledge of the stator currents. These electrical quantities are measured by current sensors, which make these elements essential for the control operation. In addition, the necessity to improve system availability, security and service continuity requires the implementation of fault tolerant control of these components.

In the following chapter, we will present the contribution of this work to the fault tolerant control of current sensors in variable speed drives using PMSMs.

Chapter III

Current Sensor Fault Tolerant Control of PMSM

3.1 Introduction

Current sensors are a key element for the successful control of an electrical drive system, which is why in this chapter two fault tolerant control techniques of current sensors will be developed, then will be applied in field oriented control on the permanent magnet synchronous machine. Different faults will be treated, namely the fault of the sensor gain, the total failure of the sensor, the dc-offset whether positive or negative, saturation of the sensor and current sensor having noise disturbance. The proposed active tolerant control encompasses a logical circuit to ensure fault detection and isolation as well as system reconfiguration in the event of a fault. It also contains a current observer to reconstruct the stator currents in order to replace faulty measurements of faulty sensors with a correct estimation. In short, the detection and isolation of faults and the reconfiguration of the system (FDIR) is an important part of systems engineering. Its primary objective is the early detection and isolation of faults, and then the reconfiguration of the system to anticipate further damage to the system and ensure the continuity of service. When a failure occurs in a system, the activation of an alarm is essential, but the emergency shutdown of the system is not always the best course of action. Therefore, simultaneous reconfiguration of this is required to allow uninterrupted operation. Whereas the proposed passive tolerant control is based on a 1st order robust controller to design the outer loop speed control to avoid the total shutdown of the system but a degradation in its performance is contingent in return.

This chapter is intended exclusively for the work carried out in both fault tolerant techniques for several current sensor faults in the PMSM drive. Then, multiple tests and simulations on the Matlab/Simulink environment of the proposed FTCs to be applied to the SPMSM used before in chapter II.

3.2 Current sensors in PMSM drives

In electrical engineering, current sensing is one of several techniques used to measure electric current. The selection of a current sensing method depends on requirements such as magnitude, accuracy, bandwidth, robustness, cost, isolation, and size.

In a typical application, the Hall sensor is used in combination with a ring-shaped soft ferromagnetic core. The hall sensor is placed in a small air gap, and the current conductor is passed through the inner part of the ferromagnetic ring. The ferromagnetic ring concentrates and amplifies the magnetic flux on the hall sensor, which generates an output voltage proportional to the current. The following table illustrates the different current sensing methods and some of their characteristics.

Method	Accuracy	Isolation	Robust	Currents	Reliability	Cost
Low (high) side current sensing	Low	No	High	Low	Low	Low
Current sensing amplifiers	High	No	High	Low	High	Low
Isolation amplifiers	High	Yes	High	Low	Low	High
Hall-effect current sensor open loop	High	Yes	Moderate	High	High	High
Closed-loop current transducers	High	Yes	High	High	High	High

Table.3.1 Summary of current measurement methods

Looking at **Table.3.1**, it can be seen that closed-loop current transducers and hall-effect current sensor have the greatest advantages. In addition, they are reliable and enable the measurement of high currents. Therefore, they are ideal for measuring the PMSM phase currents.

As discussed in section **1.3.1.2,** the current sensors are very sensitive to faults caused by: connection problems, under-voltage in the power battery, noise, offset and positive or negative gain faults, or total sensor loss [50]. They are of multiple types as modeled in **Fig.3.1**.

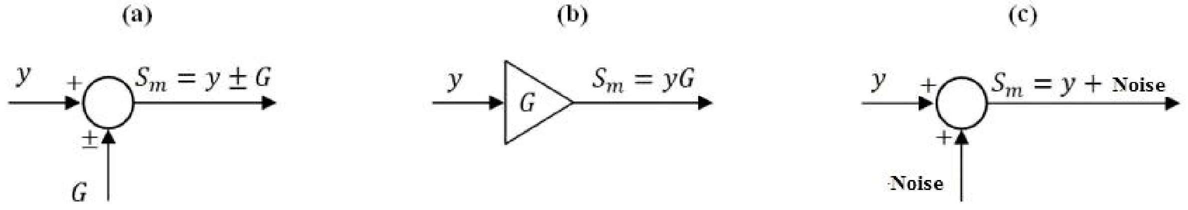


Fig.3.1 Sensor faults modeling: (a) Additive (positive or negative offset) (b) Multiplicative (gain fault or sensor total loss) (c) Disturbance (noise presence)

3.3 Active fault tolerant control of current sensor fault for PMSM

The main steps to follow when a current sensor fault occurs are to first trigger an emergency alarm, then identify the nature of the fault and then decide how to fix it. The primary role of an FTC is fault detection, location identification, decision making to isolate the faulty component, and reconfiguration of system control. However, to succeed in an active fault-tolerant control, it is necessary to ensure on one hand the detection and isolation of the fault and then the reconfiguration of the system, on the other hand, it is also necessary to succeed in reconstructing the erroneous quantities in order to guarantee the continuity of the service. It is in this context that an AFTC based on a logical circuit has been proposed to ensure the three important tasks: detection, isolation and reconfiguration. It should be noted that the reconstruction of the stator currents is based on the machine state model and some measurable quantities.

3.3.1 Estimation of stator current of PMSM with speed sensor

The architecture of the dedicated model for current reconstruction is based on that of the classic Luenberger observer [36]. Luenberger’s general theory of an adaptive observer is based on a determined system model, an adaptive mechanism for the estimated variables, and a gain matrix that ensures system stability [33, 34, 64]. However, in this work, the idea proposed for estimating stator currents using this theory is based on the conservation of the system model with the gain matrix, on the other hand, the adaptive mechanism is replaced by measurable quantities as shown in **Fig 3.2**

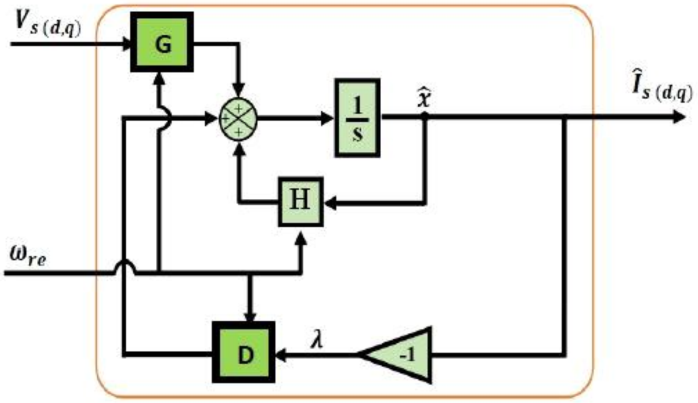


Fig.3.2 Proposed stator currents observer

This makes it possible to obtain an estimate of the stator currents at the same time efficient, simple, and stable. Therefore, to design this current observer, the PMSM dq-model presented earlier in Chapter II by equation (2.33) is used.

In machine applications, the conventional Luenberger observer has often been used for speed estimation, where the inputs are the currents and voltages and the output is the rotational speed of the machine. In our application as shown in **Fig.3.2** which aims to estimate the stator currents and not the rotation speed, the inputs will be the stator voltages and the rotation speed which replaces in turn the adaptive mechanism, on the other hand, the output will be the estimated stator currents. The stator currents estimation is based on the PMSM model and a gain matrix which is determined using some stability test [64]:

$$\dot{\hat{X}} = H\hat{X} + GU + D\lambda \tag{3.1}$$

$$[\hat{X}]^{T} = [\widehat{I_{sd}}\ \ \widehat{I_{sq}}],\ [U]^{T} = [V_{sd}\ \ V_{sq}\ \ \phi_{r}], \lambda = [I_{sd} - \widehat{I_{sd}}\ \ I_{sq} - \widehat{I_{sq}}] \tag{3.2}$$

$$H = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_{re}\frac{L_q}{L_d} \\ -\omega_{re}\frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix}; \quad G = \begin{bmatrix} \frac{1}{L_d} & 0 & 0 \\ 0 & \frac{1}{L_q} & -\frac{\omega_{re}}{L_q} \end{bmatrix}; \quad D = \begin{bmatrix} -k\frac{R_s}{L_d} & 0 \\ 0 & -k\omega_{re} \end{bmatrix} \tag{3.3}$$

Where k is a positive constant and the ^ sign is used to express the estimated quantities.

3.3.2 Fault detection, isolation and reconfiguration in AFTC

In the proposed active fault-tolerant control method against current sensors failure, measuring of the line currents I_a, I_b, and I_c is performed by three Hall effect current sensors (sensor-*a*, sensor-*b*, and sensor-*c*) placed in the corresponding phases *a*, *b*, and *c*. However, the estimation is carried out by the proposed stator currents observer previously presented in **Fig.3.2**.

The logic circuit presented in **Fig.3.5** is intended to ensure the fault detection (FD), by analyzing the filtered residual signal between measured and estimated quantities. The resulted signal will be inputted to the absolute value block so that it which will be compared only to one positive threshold value (Th=0.5A) that is empirically determined by assuming a threshold of 20% (or less by using different tests to the machine) of PMSM rated stator current [63].

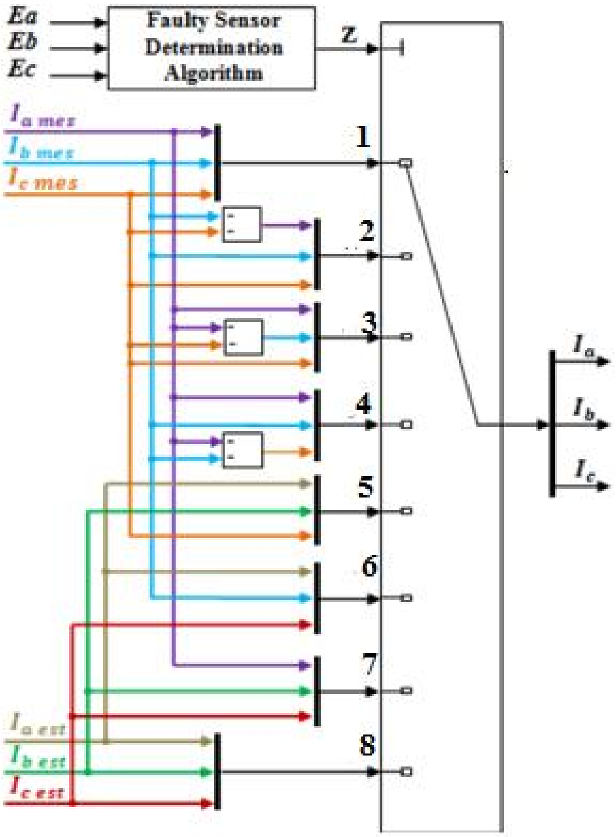


Fig.3.3 Current sensors fault detection, isolation and reconfiguration mechanism: multi-port switch for proper reconfiguration of a, b, and c

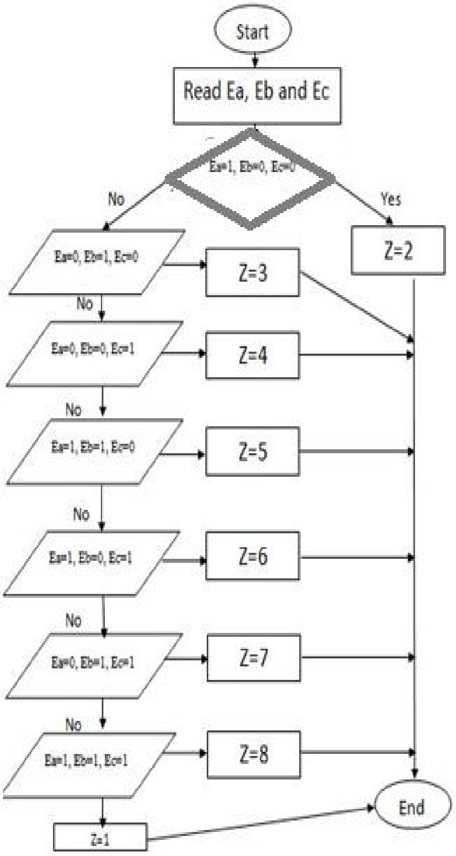


Fig.3.4 Flow-chart of faulty sensors determination algorithm

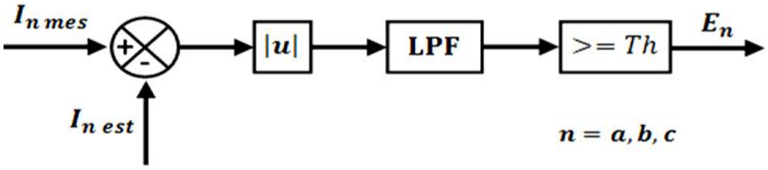


Fig.3.5 Faults detection circuit

At every sampling instant, the FD logic circuit generates three impulses *Ea*, *Eb* and *Ec* as follows:

$$E_n = \begin{cases} 0 & \text{if } I_n \text{ is in Healthy state} \\ 1 & \text{if } I_n \text{ is in Faulty state} \end{cases} \quad \text{with: } n = a, b, c.$$

These three impulses (*Ea*, *Eb*, and *Ec*) are passed into an algorithm that allows generating an index *Z* (**Fig.3.4)**. Depending on the sensor states, this index can takes integer values from 1 to 8. The different possible combinations of sensor states are summarized in **Table.3.2**. According to *Z* values in **Fig.3.4**, a multi-port switch is used to select the proper current components to replace the missing sensor's information (see **Fig.3.3**). It is clear that in the case of only one faulty current sensor, the missing current data will be replaced by the measurements from the two other healthy sensors by applying Kirchhoff's currents law to the neutral node as in (3.3) while using the observer block information when 2 or more sensors are failed.

$$I_{a\,mes} + I_{b\,mes} + I_{c\,mes} = I_N = 0 \tag{3.3}$$

Phase-a sensor	Phase-b sensor	Phase-c sensor	Z	Proper selected currents
Faulty	Healthy	Healthy	2	$-(I_{b\,mes}+I_{c\,mes})$, $I_{b\,mes}$ and $I_{c\,mes}$
Healthy	Faulty	Healthy	3	$I_{a\,mes}$, $-(I_{a\,mes}+I_{c\,mes})$ and $I_{c\,mes}$
Healthy	Healthy	Faulty	4	$I_{a\,mes}$, $I_{b\,mes}$ and $-(I_{a\,mes}+I_{b\,mes})$
Faulty	Faulty	Healthy	5	$I_{a\,est}$, $I_{b\,est}$ and $I_{c\,mes}$
Faulty	Healthy	Faulty	6	$I_{a\,est}$, $I_{b\,mes}$ and $I_{c\,est}$
Healthy	Faulty	Faulty	7	$I_{a\,mes}$, $I_{b\,est}$ and $I_{c\,est}$
Faulty	Faulty	Faulty	8	$I_{a\,est}$, $I_{b\,est}$ and $I_{c\,est}$
Healthy	Healthy	Healthy	1	$I_{a\,mes}$, $I_{b\,mes}$ and $I_{c\,mes}$

Table.3.2 Phase sensors fault determination with proper selection of corrected value of *a*, *b*, and *c* currents

3.4 Passive FTC of current sensor fault for PMSM using robust controller

Passive fault-tolerant control is based on robust controller design techniques. To succeed in a passive fault-tolerant control, it is necessary to have a controller that makes the closed-loop system insensitive to certain faults. This approach requires no online detection of the faults which is computationally attractive but very restricted due to the decrease in the performance of the system to achieve an increased robustness to certain faults. The proposed speed controller in this thesis is based on the 1st order sliding mode control theory.

3.4.1 Sliding mode control theory

The SMC is a variable structure control method which is widely known in the automatic and control field. The strength points of the SMC are the robustness against uncertainties, fast response and simple software and hardware implementation [58, 59]. SMC bases on forcing the system trajectory to slide along a switching surface under determined control law. It consists of two phases, a reaching phase where the state trajectory is driven to the surface S= 0 and reaches it in a finite time, followed by a sliding phase where it slides on the switching surface to an equilibrium point, as shown in **Fig.3.6** [67].

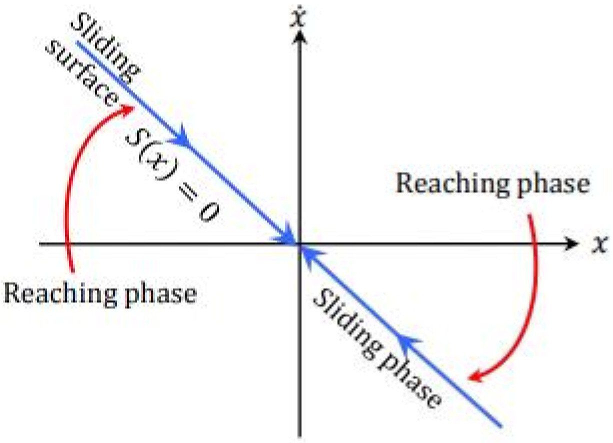


Fig.3.6 Sliding mode principle of state trajectory [67].

The design of SMC can be achieved into two phases. The first phase is determining the switching surface. In engineering applications, the error between control objectives and the reference inputs and its derivative is used to form the sliding surface [68]. The second phase is to design the control law in a way that to steer the system trajectory to the sliding surface [69, 70]. The well applied sliding surface was proposed by Slotine as:

$$S = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \tag{3.4}$$

Where S is the sliding surface, λ is positive constant, *e* is the system error and n is the system relative order. The sliding mode must exist in all points of the surface S = 0. To guarantee that the system state stays in sliding mode after the reaching phase, the existence conditions should be:

$$\begin{cases}\lim_{n\to 0^-} \dot{S} < 0 \\ \lim_{n\to 0^+} \dot{S} > 0\end{cases} \tag{3.5}$$

It means that if S is positive, then its derivative should be negative and if S is negative, then its derivative should be positive. It can be written in a simplified way as:

$$S\dot{S} < 0 \tag{3.6}$$

Since the existence problem looks like a generalized stability problem, it can be summarized in terms of Lyapunov's theory as the follows [71]:

$$V = \frac{1}{2}S^2 \tag{3.7}$$

The aim is to determine a control law such that $\dot{V} < 0$ in order to drive the system states to the sliding-mode surface:

$$\dot{V} = S\dot{S} < 0 \tag{3.8}$$

when $S \neq 0$, $\dot{V}$ is negative definite. Therefore, for finite time convergence the condition (3.8) ensures asymptotically convergence towards the sliding surface.

3.4.2 First order SM-speed controller design

In this section, first order sliding mode controller will be designed for speed regulation loop to generate the electromagnetic toque reference and to ensure good dynamic and fast response while the control design principle is discussed in **Appendix C**. The sliding surface of the rotor speed is defined by:

$$\begin{cases}S_{\omega_r} = \omega_r^* - \omega_r \\ \dot{S}_{\omega_r} = \dot{\omega}_r^* - \dot{\omega}_r\end{cases} \tag{3.9}$$

The mechanical equation of induction motor is given as:

$$\dot{\omega}_r = \frac{1}{J}(T_e - T_L) - \frac{f}{J}\omega_r \tag{3.10}$$

By substituting the equation (3.10) in the equation of the speed surface derivative, it will be given as follows:

$$\dot{S}_\omega = \dot{\omega}_r^* - \frac{1}{J}(T_e - T_L - f\omega_r) \tag{3.11}$$

Basing on sliding mode theory, we can write:

$$T_e = T_{eeq} + T_{en} \tag{3.12}$$

The equivalent control part is defined during the sliding mode state $\dot{S}\omega=0$, then the equivalent control:

$$T_{eeq} = f\omega_r + T_L \tag{3.13}$$

The discontinuous part is defined as:

$$T_{en} = K_{\omega_r} sign(S_{\omega_r}) \tag{3.14}$$

3.5 Simulation of the FOC-SVM for SPMSM with current sensor faults

As mentioned previously in chapter II, the results of the first simulation represent an image of a healthy electric drive system and those results are sufficient and reliable to be compared with in case of some failures in the SPMSM drive system. It is necessary to know the effects of several current sensor faults on the whole system's performance and stability in order to choose the best, suitable tolerant control system to these faults. Thus, a simulation of FOC-SVM under some current sensor faults without a tolerant system was conducted.

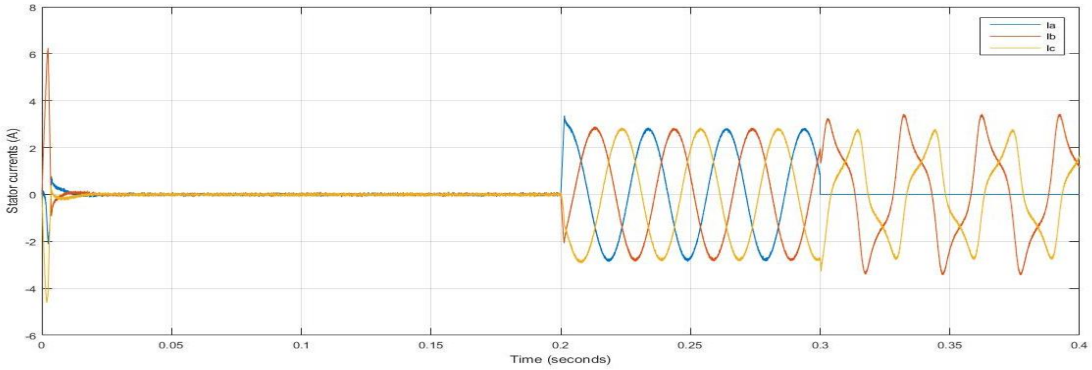
This simulation of t=0.4sec can be conducted using the same Simulink block of chapter II (**Fig.2.20**) (Full load torque of 2.5N.m at t=0.2sec) with an addition of some fault events while relinquishing the tolerant system in order to see, study and analyze the effect of failed current sensors on the system's performance, stability and security. The fault events to be tested for this simulation are the total loss of current sensor a (stator phase a current sensor), gain fault in current sensor a (30%) and the DC-offset fault in current sensor a (+0.5A).

3.5.1 Simulation results and analysis

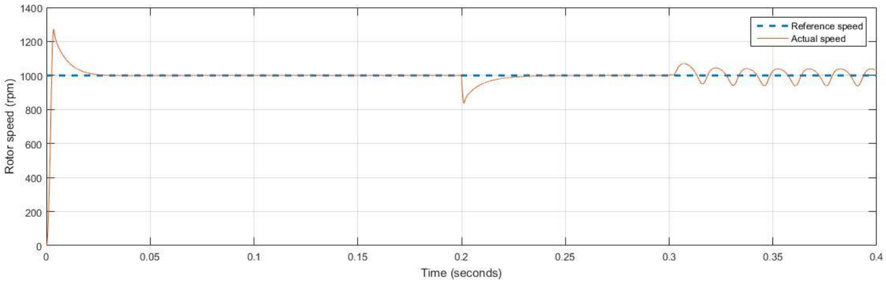
The following figures (**Fig.3.7, Fig.3.8, Fig.3.9**) represent the results of simulation with an application of several faults on the stator current sensor a at t=0.3sec.

- **Total loss of current sensor a**

(a)



(b)



(c)

(d)

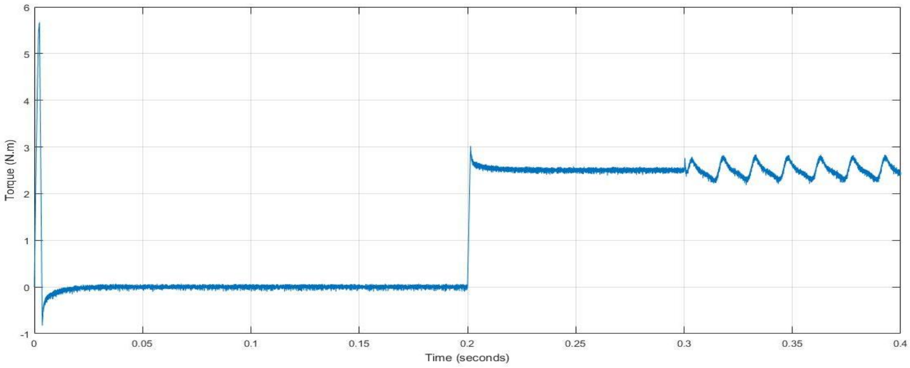
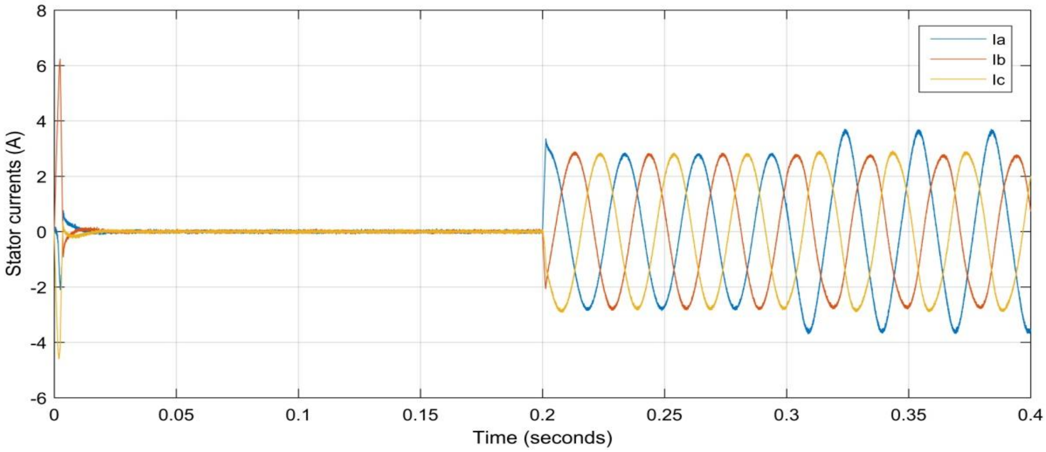


Fig.3.7 Simulation results of the FOC-SVM for SPMSM with total loss of current sensor a: (a) Three phase currents (b) Speed response (c) d-q current components (d) Torque response

- **Gain fault (30%) in current sensor a**

(a)



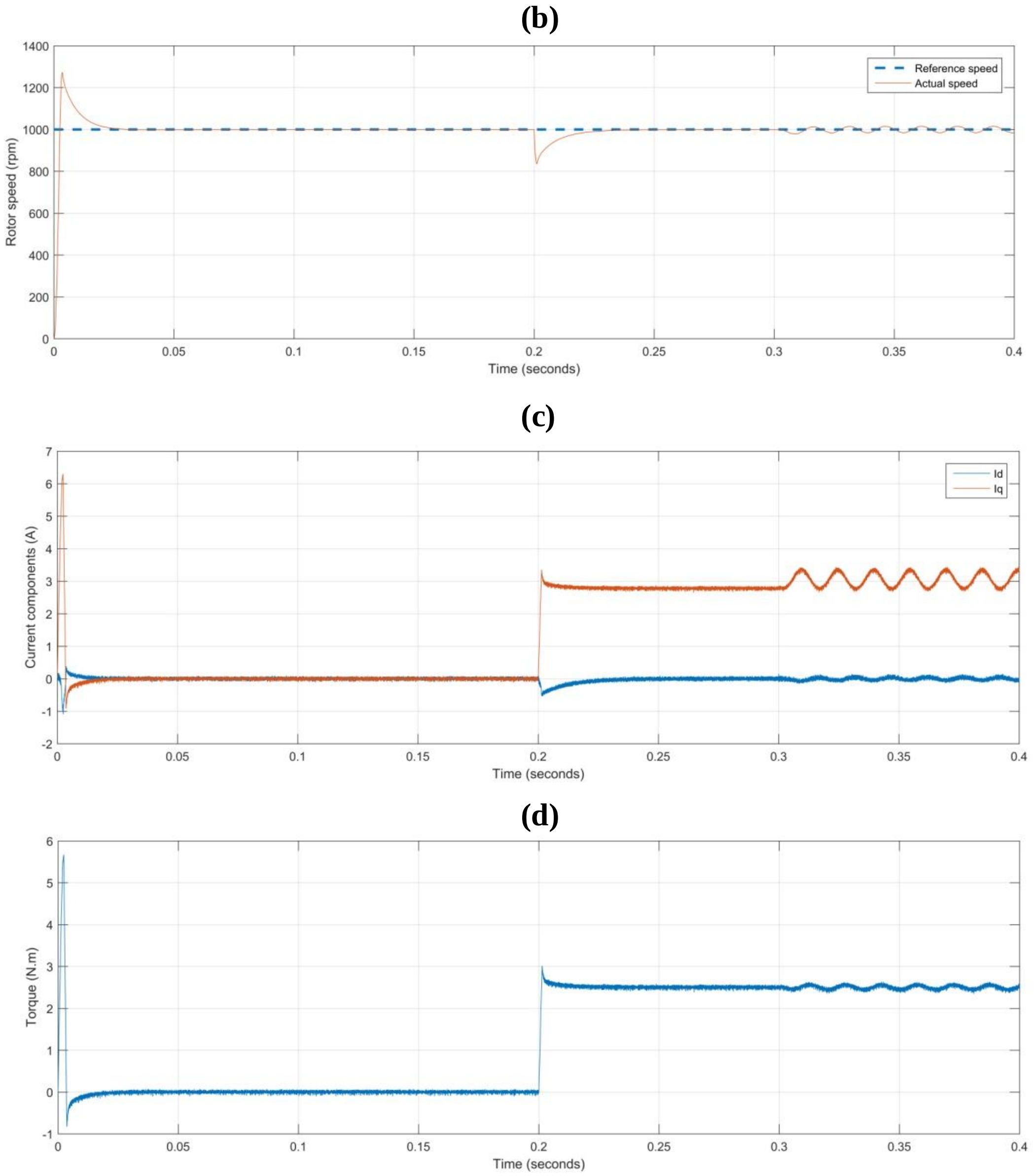
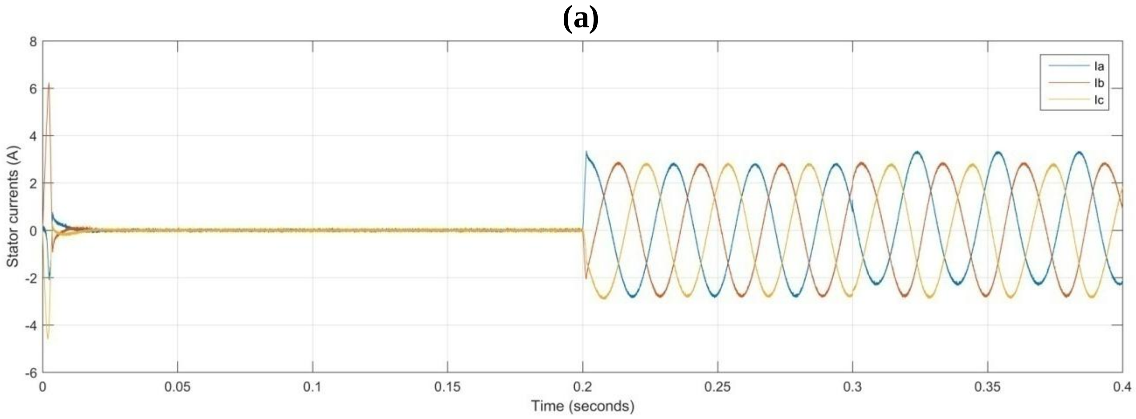
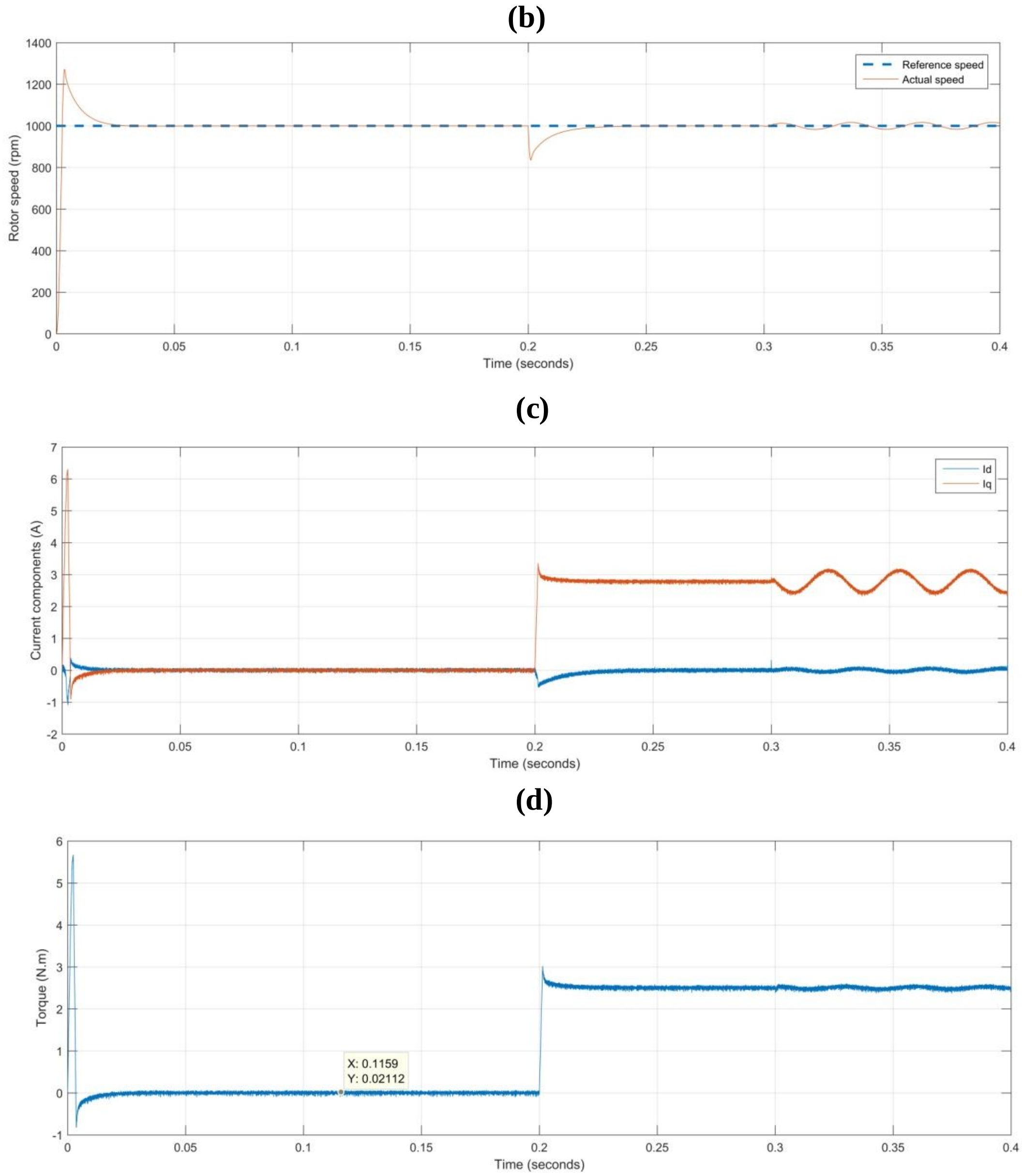


Fig.3.8 Simulation results of the FOC-SVM for SPMSM with gain fault (30%) of current sensor a: (a) Three phase currents (b) Speed response (c) d-q current components (d) Torque response

- **DC-offset fault in current sensor a (+0.5A)**




(b)

(c)

(d)

Fig.3.9 Simulation results of the FOC-SVM for SPMSM with DC-offset fault (+0.5A) of current sensor a: (a) Three phase currents (b) Speed response (c) d-q current components (d) Torque response

The stator current I_a is affected by the several faults applied on its sensor, as no signal appears when the total loss of the signal, higher peak-to-peak value comparing to its healthy state when gain fault was applied and a positive shift in its magnitude due to the DC-offset shift in the sensor readings. The other 2 stator currents were not affected in the last two tests but were highly affected when the total loss fault of the sensor was applied since the Kirchhoff's currents law won't exist anymore. Those false results will affect the d-q current components as shown in the three previous figures and hence the PI controllers which leads to high ripples in the produced torque which causes speed oscillations that contradicts with the advantage of PMSMs. The high speed oscillations could damage the motor shaft and the whole drive leading to a disaster that could harm the drive environment. This simulation had several tests only to the stator current sensor a and its result were not promising since the PMSM's performance decreased and its stability is not guaranteed. Hence, the PMSM is neither reliable nor secure anymore. Further damage could be seen when applying these faults or others simultaneously or successively on the sensors.

3.5.2 Simulation results conclusion

After reaching good results and responses to control commands for the permanent magnet synchronous machine in chapter II, a necessity to develop a fault tolerant control system is looming in order to increase the reliability, security and availability of the whole system. This necessity is demanded because of the weak response of the system in the event of current sensor faults in the absence of the tolerant control system. Especially that these faults destabilize the system's security and performance and cannot be rid unless the components are changed (hardware redundancy), tolerated (passive tolerant control system based on software redundancy) or reconfigured (active tolerant system based on software redundancy) which is the work done in the next simulations.

3.6 Simulation of the PFTC of SPMSM with current sensor fault

Fig.3.10 presents the Simulink block of the passive fault tolerant control for multiple current sensor faults based on 1st order SM speed controller in SPMSM with FOC-SVM control technique where the only difference between the non-tolerated FOC-SVM system and the tolerated one is in the outer loop design.

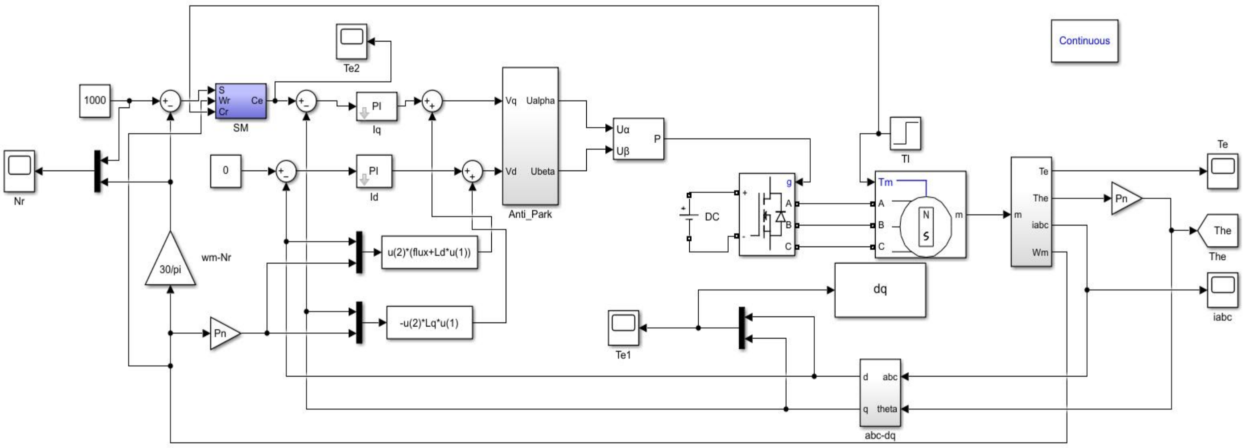


Fig.3.10 Simulink block of the proposed PFTC against current sensors failures in SPMSM

3.6.1 Simulation results and analysis

The figure (**Fig.3.11**) represents the results of simulation of the PFTC of SPMSM with total loss fault in current sensor a at t=0.3sec.

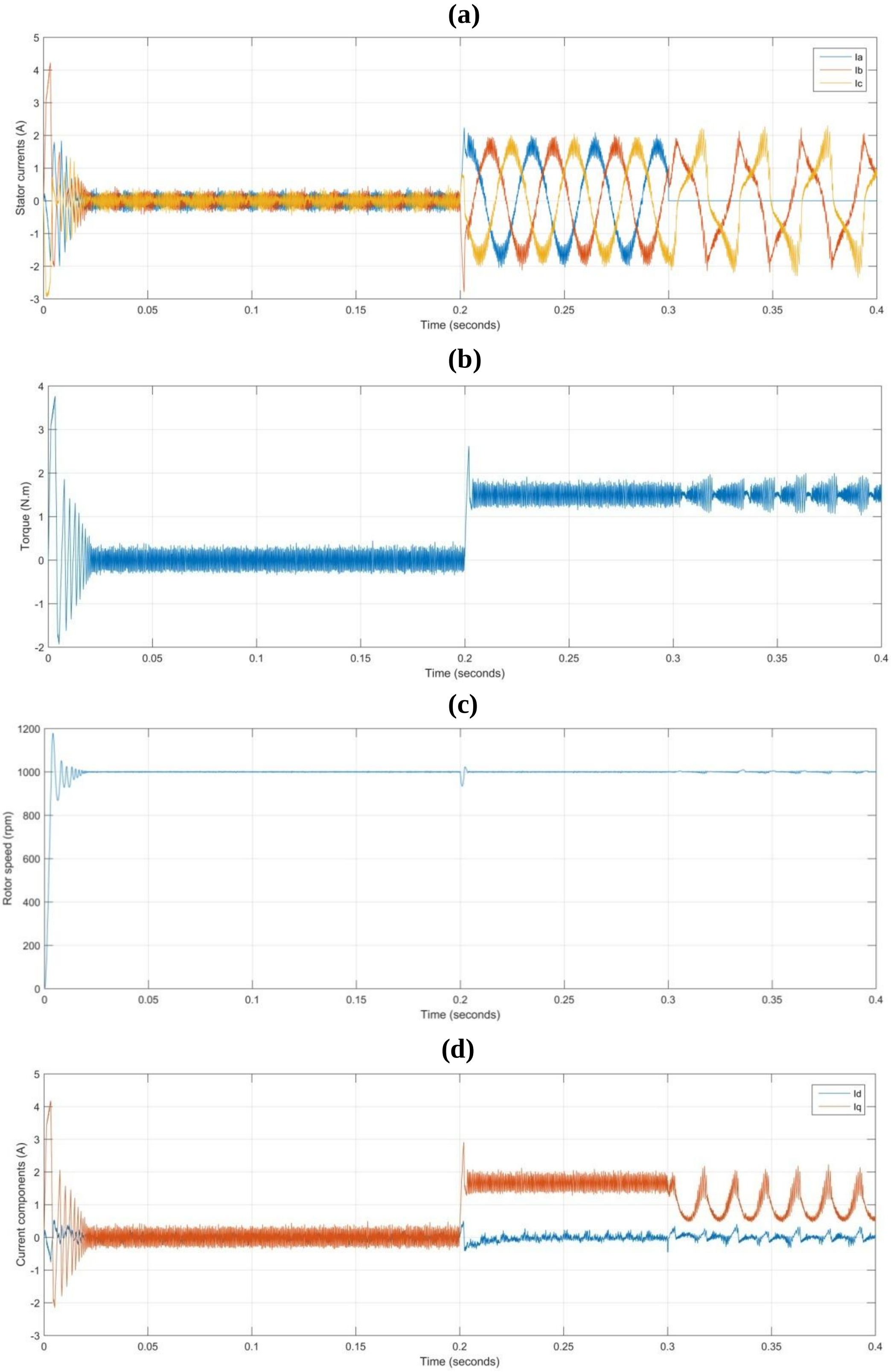


Fig.3.11 Simulation results of PFTC of SPMSM with total loss fault in current sensor a: (a) Three phase currents (b) Torque response (c) Speed response (d) d-q current components

The simulation results of the PFTC to the current sensor faults are acceptable in a way. The 1st order SM speed controller had a good robustness against the total loss failure of the sensor since the actual rotor speed was following the reference command and was unaffected by the failure in the sensor. In contrast, high oscillations in the d-q current components can be classified as an apparent effect of the fault due to the loss and non-recovery of the lost signal. As result, the chattering effect was highly present in the produced torque. The chattering effect can be noticed before fault application due to the SM design principle. It can be concluded that what remains in designing a SM speed controller in PMSMs is to find balance between the robustness and the chattering for wide range of operating conditions. In other words, having a good robustness to several current sensor faults while having constant performance.

3.6.2 Simulation results conclusion

The results of the proposed PFTC are acceptable under several current sensor failures due to the good robustness of the SM speed controller that appeared in the rotor speed response. To improve the design of such controllers, 2nd order SM could be used. The PFTC of certain current sensor faults is attractive in some domains due its simplicity in design and efficiency under these faults. It could also be unattractive in other domains due to its side effects and its fault type dependent design. Another tolerant technique is the AFTC can be used; it preserves the system's performance and increases the system's dependability under every current sensor fault. The results of the AFTC simulation to be discussed in the next section.

3.7 Simulation of the AFTC of SPMSM with current sensor faults

Since the results of the previous simulations did not guarantee neither the system's consistent service continuity nor the system's stability and security in the presence of some fault events, an active fault tolerant control system must be added in order to ensure the system continuity of service under any current sensor failures by the software reconfiguration of lost components signals and to detect the faults in order to increase the drive's system reliability, availability and security.

Simulation of the AFTC of SPMSM with current sensor faults to be conducted by converting the block of **Fig.3.12** to a Simulink block as shown in **Fig.3.13** with an addition of some fault events.

The simulation results will also be compared to the healthy electric drive system response and to the PFTC simulation results in order to test if the objectives of this AFTC are achieved.

Fig.3.12 shows the diagram of the vector control (FOC-SVM) of the SPMSM, active tolerant to the faults in the current sensors.

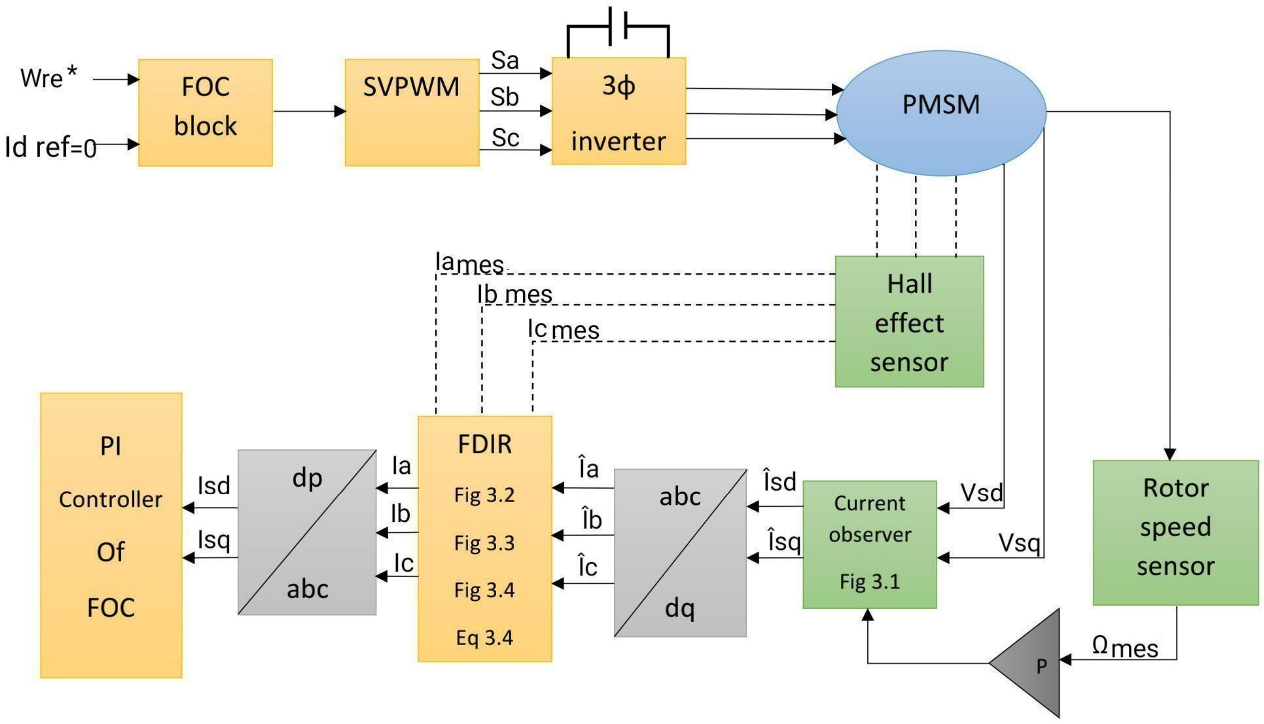


Fig.3.12 Scheme of the proposed AFTC against current sensors failures in SPMSM

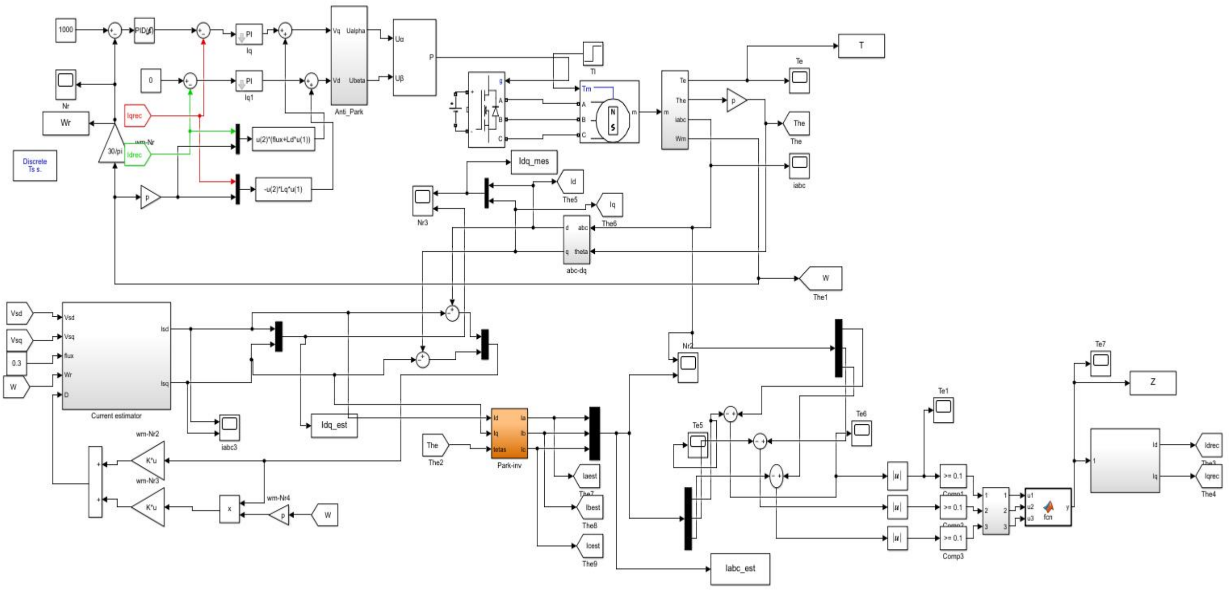


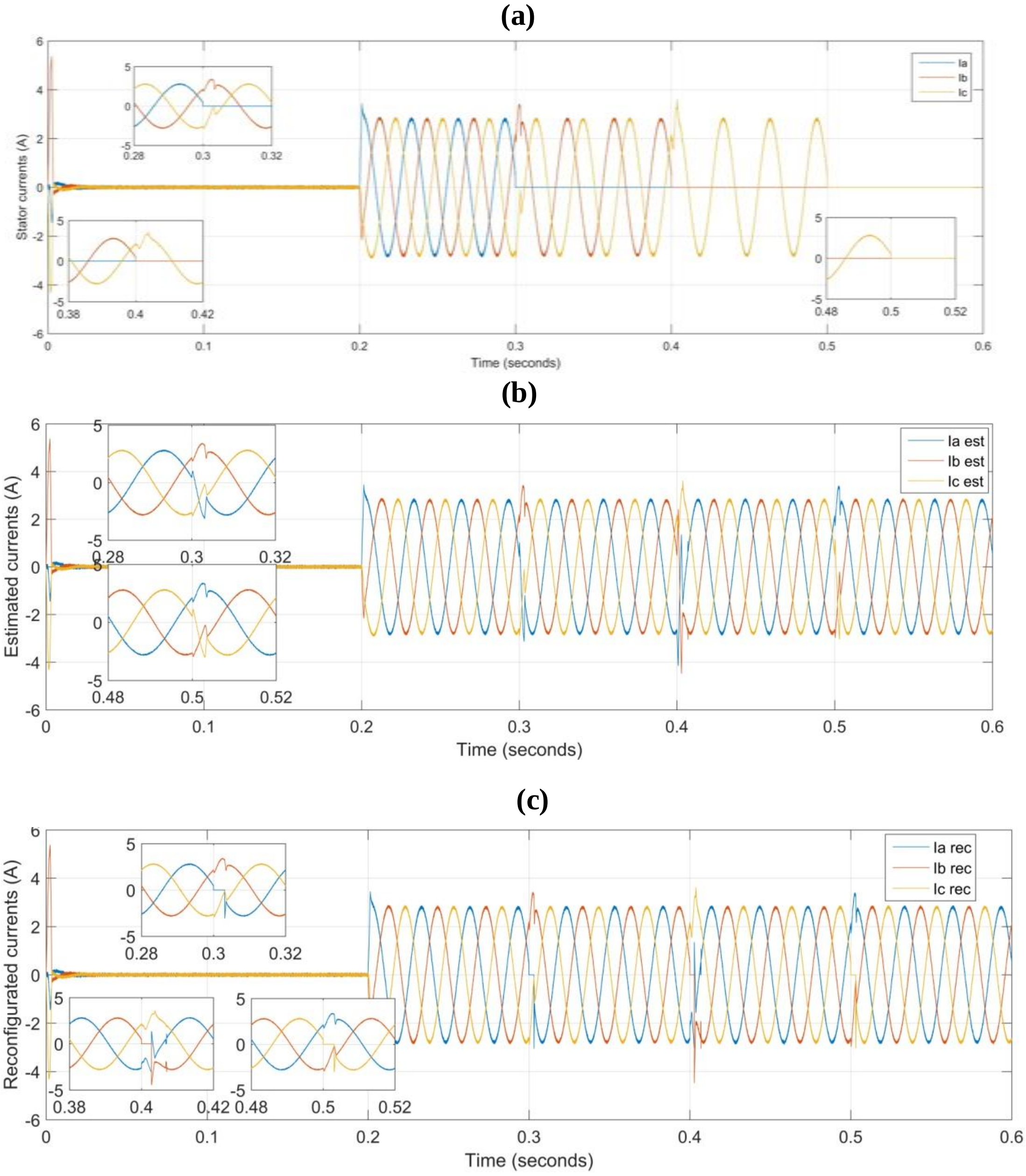
Fig.3.13 Simulink block of the proposed AFTC against current sensors failures in SPMSM

The Simulink block shown in the figure (**Fig.3.13**) consists of four important blocks: FDI, current observer, FR and the FOC system where the inputs of the current PI controllers are the outputs of the FDIR block and this is to ensure always the service continuity in case of a fault event or even in the healthy state in anticipation of faults. Several faults can be applied to test the effectiveness of the whole system. Failures of the three current sensors is the best case to test if the AFTC is efficient in guaranteeing the system's continuity of service as well as its security while the occurrence of any type of faults. If so, the AFTC will provide a current sensorless vector control to the PMSM.

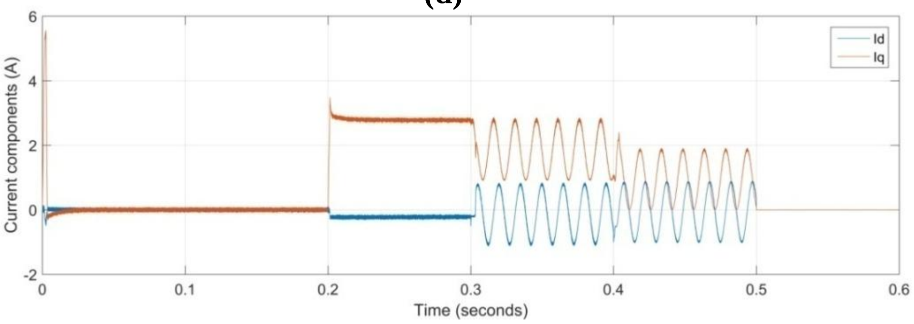
3.7.1 Simulation results and analysis

The following figures (**Fig.3.14, Fig.3.15, Fig.3.16, Fig.3.17**) represent the results of simulation under several current sensor faults based on the a-b-c sequence at different times.

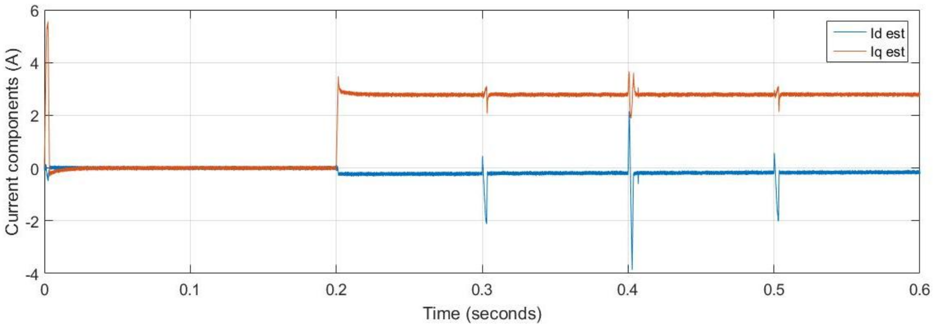
- **Successive total loss failure in the three current sensors**



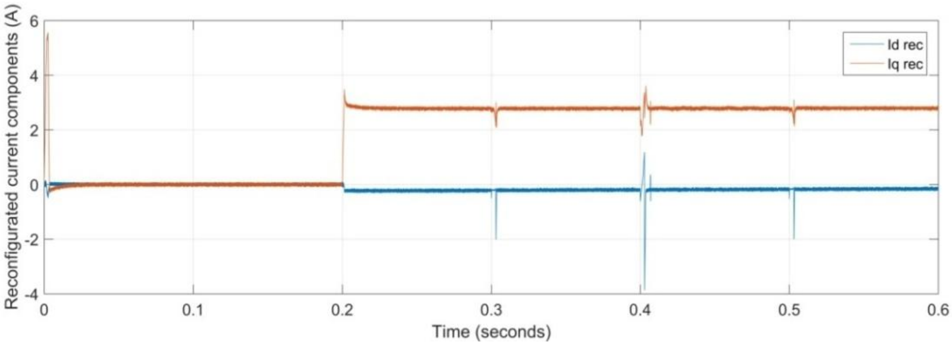
(d)


Id
Iq
Current components (A)
6
4
2
0
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

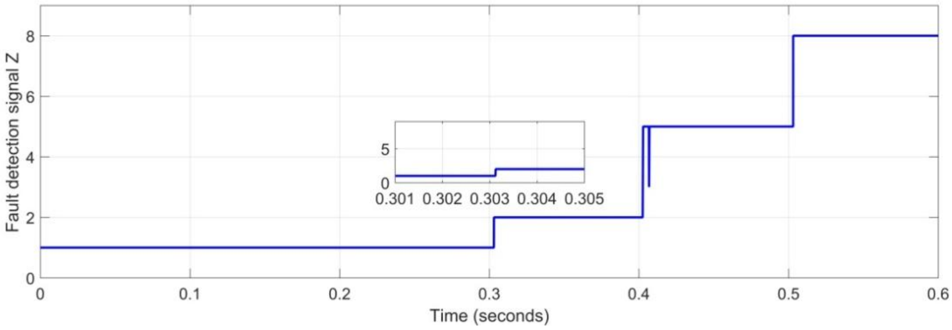
(e)


Id est
Iq est
Current components (A)
6
4
2
0
-2
-4
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

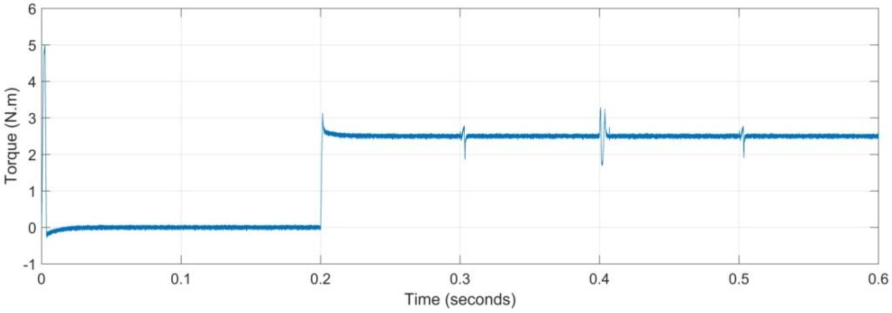
(f)


Id rec
Iq rec
Reconfigurated current components (A)
6
4
2
0
-2
-4
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(g)


Fault detection signal Z
8
6
4
2
0
5
0
0.301
0.302
0.303
0.304
0.305
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(h)


Torque (N.m)
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(i)

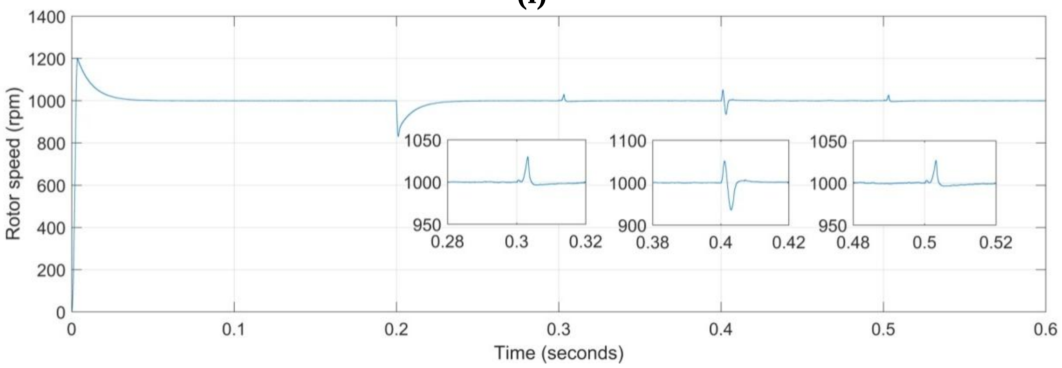
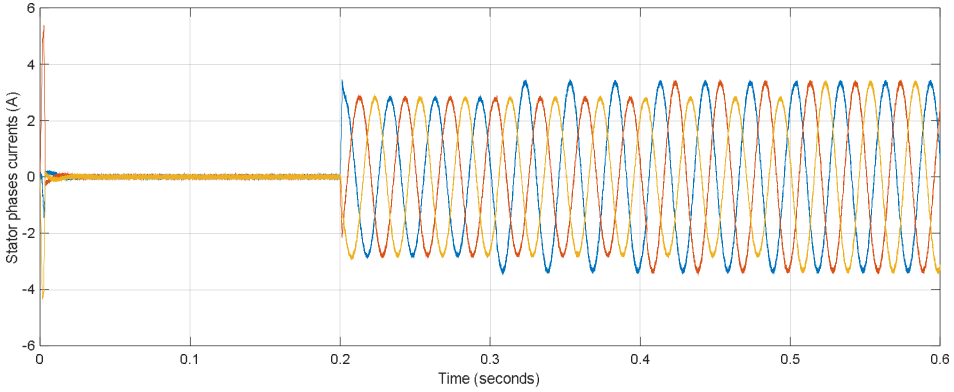


Fig.3.14 Simulation results of AFTC of SPMSM with successive total loss failure in all sensors: (a) Measured abc currents (b) Estimated abc currents (c) Reconfigured abc currents (d) Measured d-q currents (e) Estimated d-q currents (f) Reconfigured d-q currents (g) FDI output (h) Torque response (i) Speed response

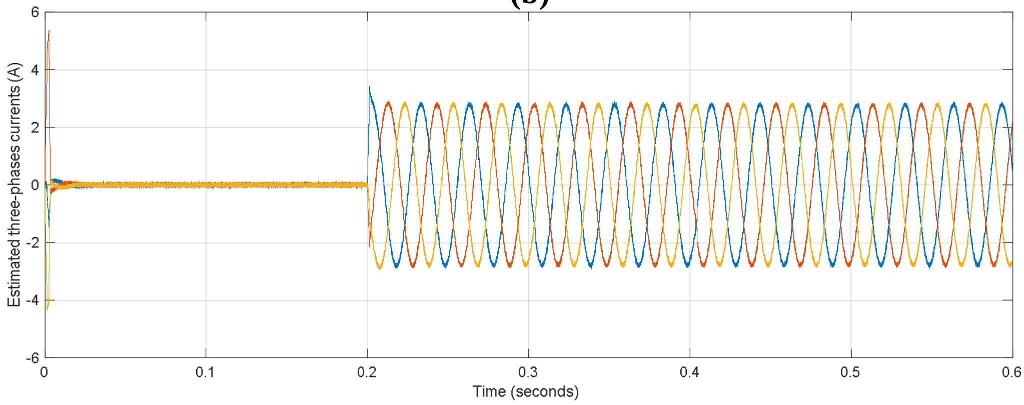
Fig.3.14 illustrates the results of simulation for the proposed AFTC system that was applied on PMSM, the fault event in this test is the successive total loss in all sensors. Since this tolerant control system is based on software redundancy, no hardware components are going to be used. Thus, no successive change in sensors. After a short time (0.005sec) beyond t=0.3sec, The FDIR block reacts by giving an output signal Z=2 (in FDI block) replacing this faulty measured current by the correct current signal (in FR block) knowing that the current observer is not used by the FDIR yet. After a short time beyond t=0.4sec, The FDIR block reacts by giving an output signal Z=5 replacing the two measured currents by the correct current signals by the use of current observer. At t=0.5sec, The FDIR block reacts by giving an output signal Z=8 replacing all measured currents by the correct current signals from the observer. Despite having successive failures in a small amount of time in all sensors, the PMSM still work (good response to control commands as shown in the speed and torque responses thus continuity in service) and is not affected by total loss in current sensors anymore.

- **Successive positive gain failure in the three current sensors**

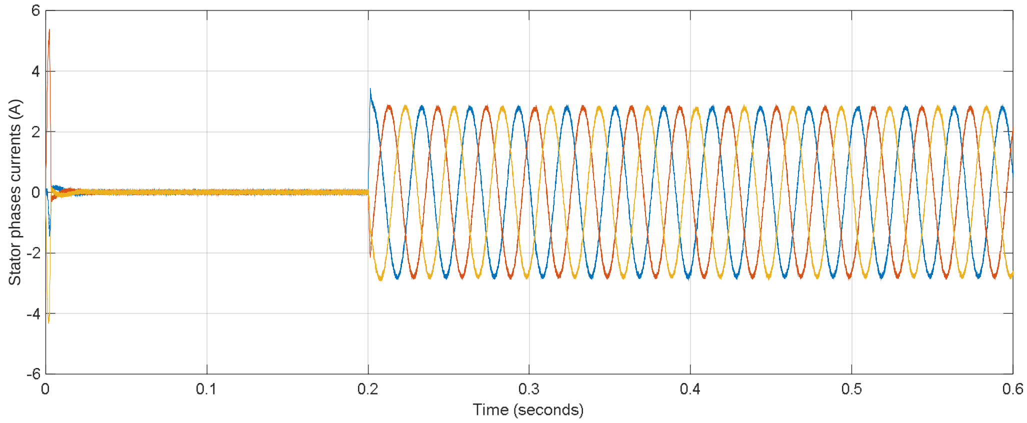
(a)



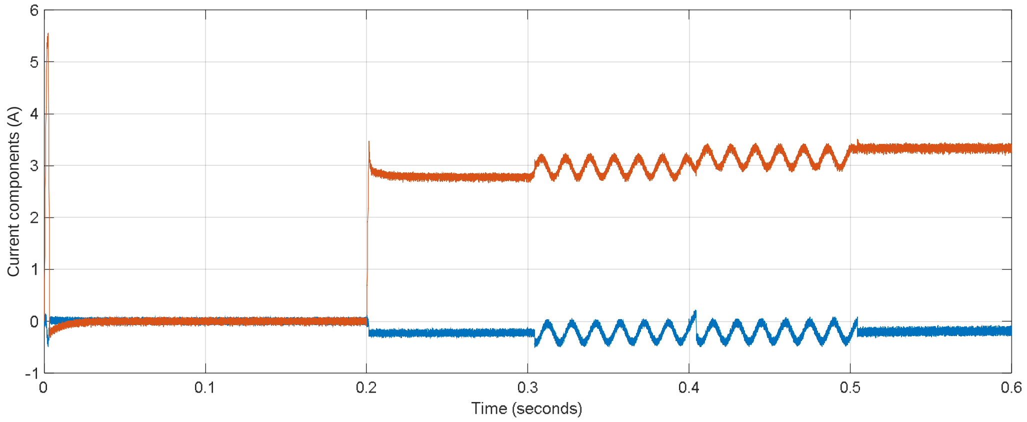
(b)


Estimated three-phases currents (A)
6
4
2
0
-2
-4
-6
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

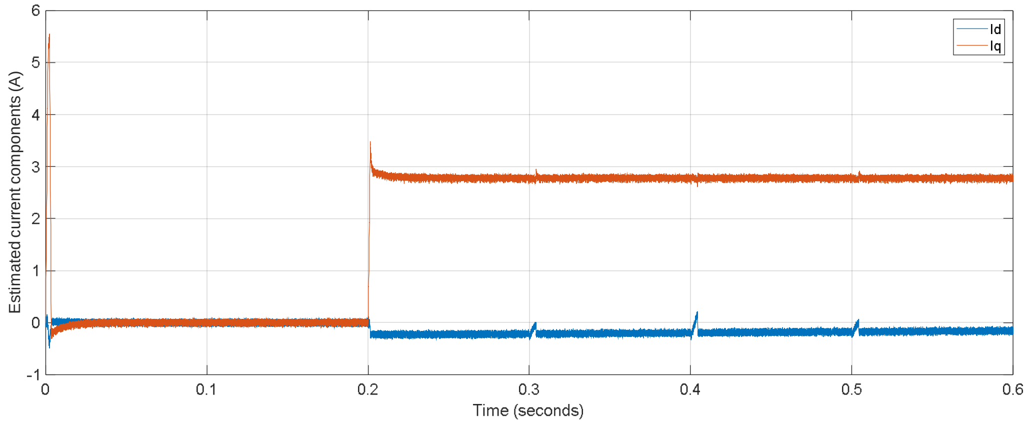
(c)


Stator phases currents (A)
6
4
2
0
-2
-4
-6
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

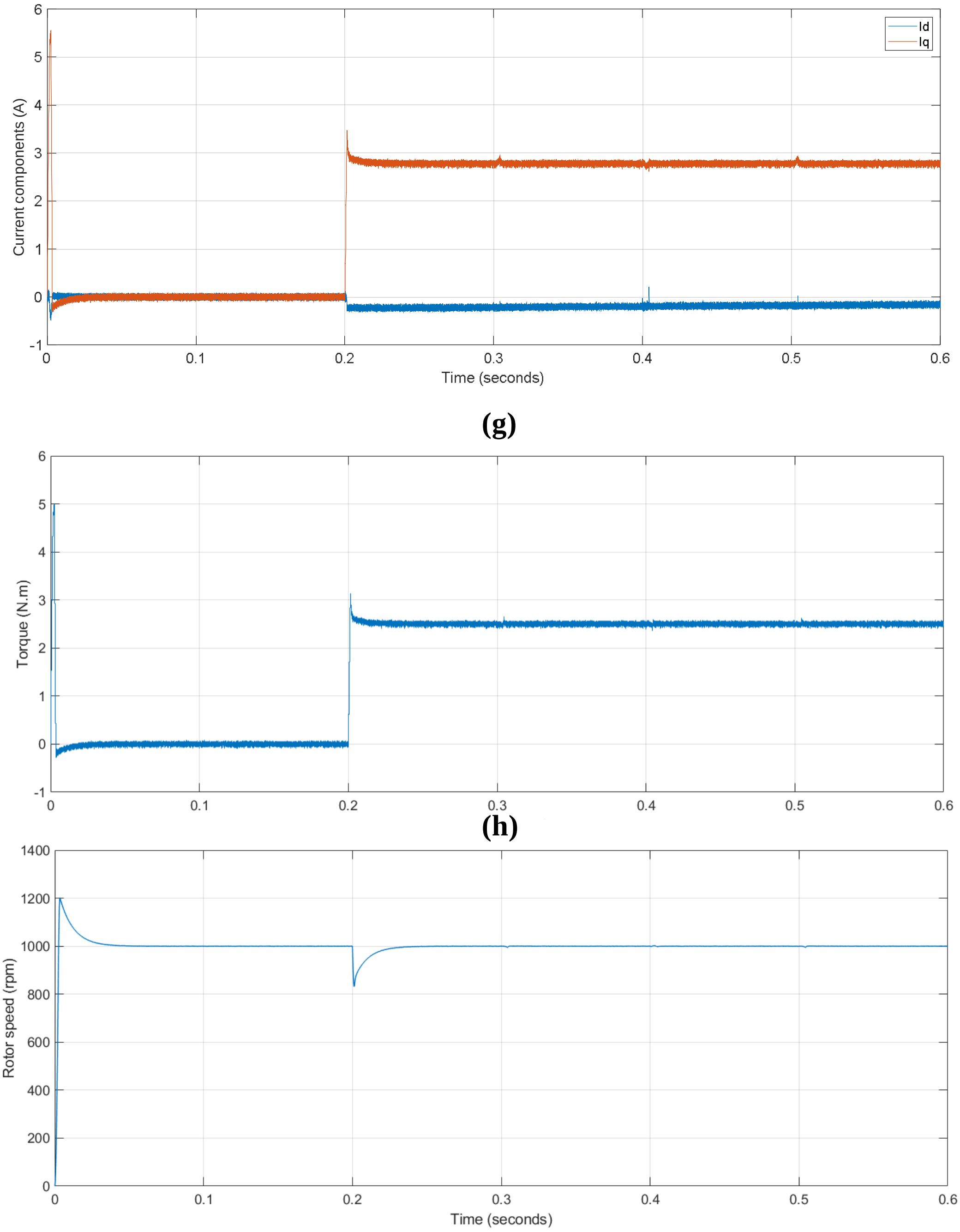
(d)


Current components (A)
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(e)


Estimated current components (A)
Id
Iq
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(f)



(g)

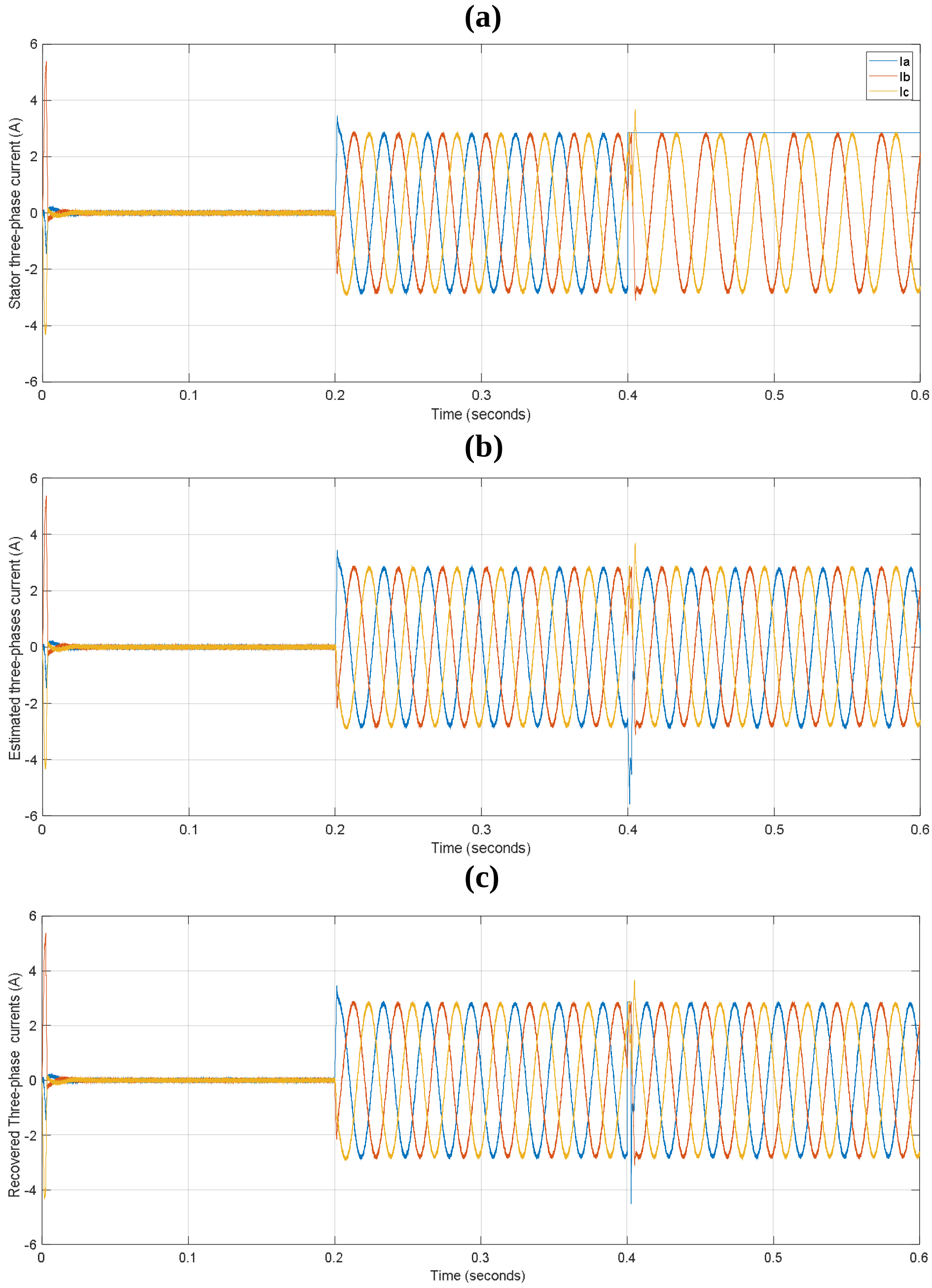
(h)

Fig.3.15 Simulation results of AFTC of SPMSM with successive gain failure in all sensors: (a) Measured abc currents (b) Estimated abc currents (c) Reconfigured abc currents (d) Measured d-q currents (e) Estimated d-q currents (f) Reconfigured d-q currents (g) Torque response (h) Speed response

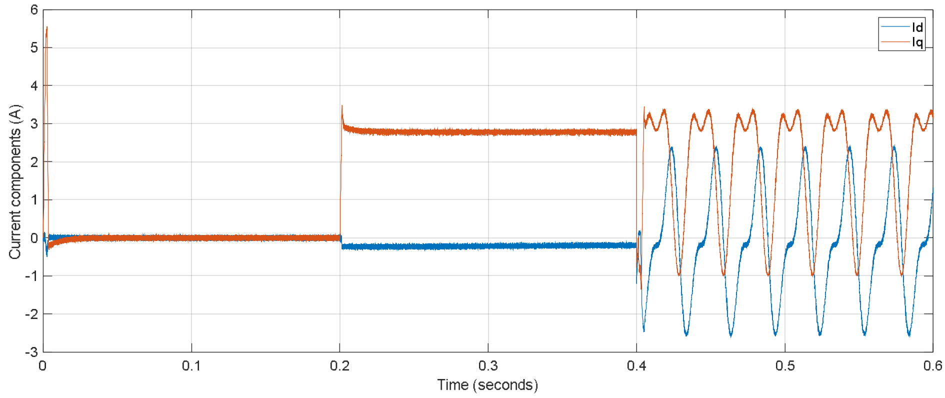
Fig.3.15 illustrates the results of simulation for the proposed AFTC system that was applied on PMSM, the fault event in this test is the successive gain failures in all sensors. After a short time (0.005sec) beyond t=0.3sec, The FDIR block reacts by giving an output signal Z=2 (in FDI block) replacing this faulty measured current by the correct current signal (in FR block) knowing that the current observer is not used by the FDIR yet. After a short time beyond t=0.4sec, The FDIR block reacts by giving an output signal Z=5 replacing the two measured currents by the correct current signals by the use of current observer. At t=0.5sec, The FDIR block reacts by giving an output signal Z=8 replacing all measured currents by the correct current signals from the observer. At t=0.5sec, another thing can be noticed is that all stator currents are having amplified healthy shape but the fault still exist which is why the FDI block is important in this system. To conclude, the PMSM is not affected by gain faults in current sensors anymore.

The output signal Z of the FDI block is not shown in **Fig.3.15** as it is the same as in **Fig.3.14** by applying the fault successive sequence a-b-c.

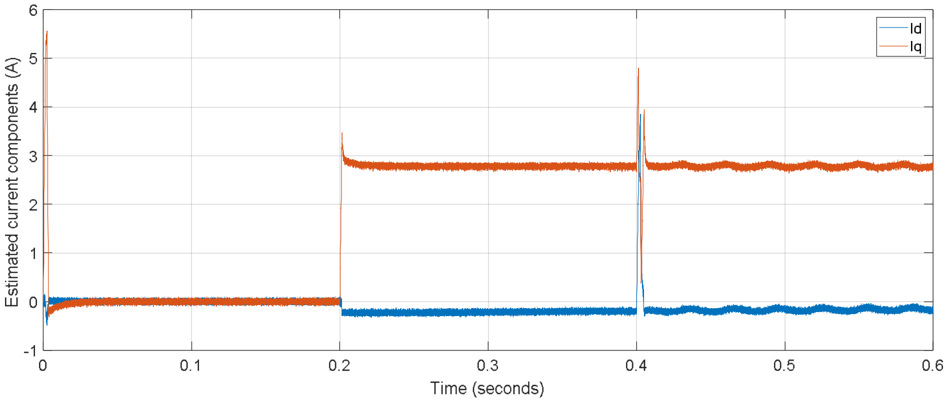
- **Saturation of current sensor a**



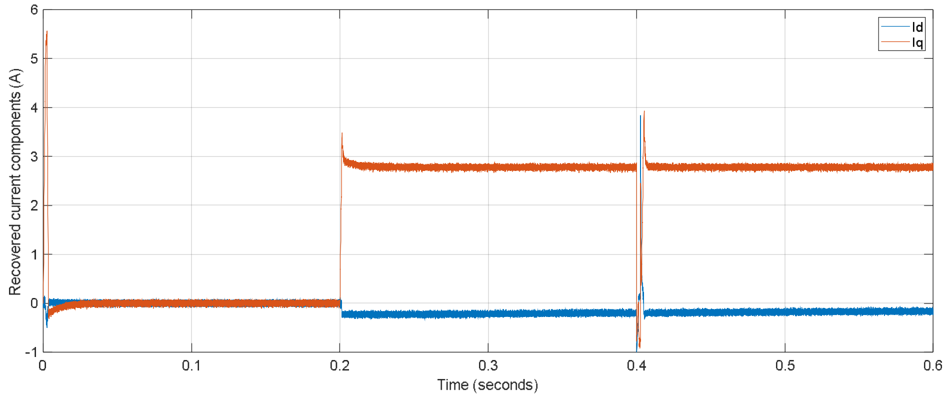
(d)


Id
Iq
Current components (A)
6
5
4
3
2
1
0
-1
-2
-3
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

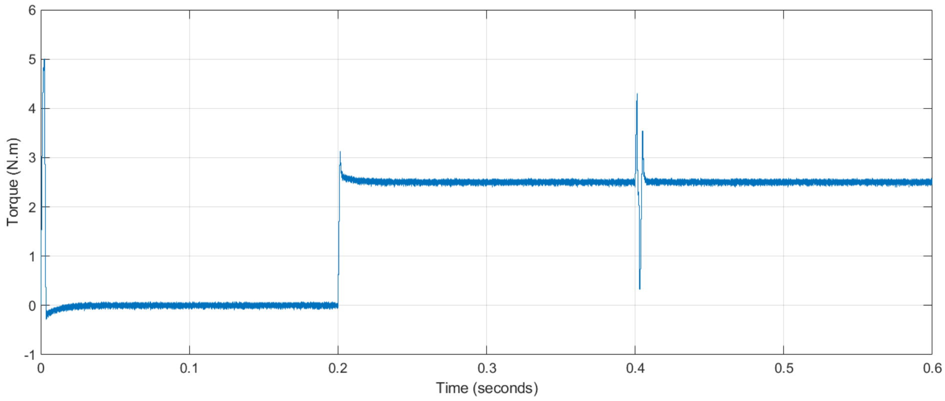
(e)


Id
Iq
Estimated current components (A)
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(f)


Id
Iq
Recovered current components (A)
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(g)


Torque (N.m)
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(h)

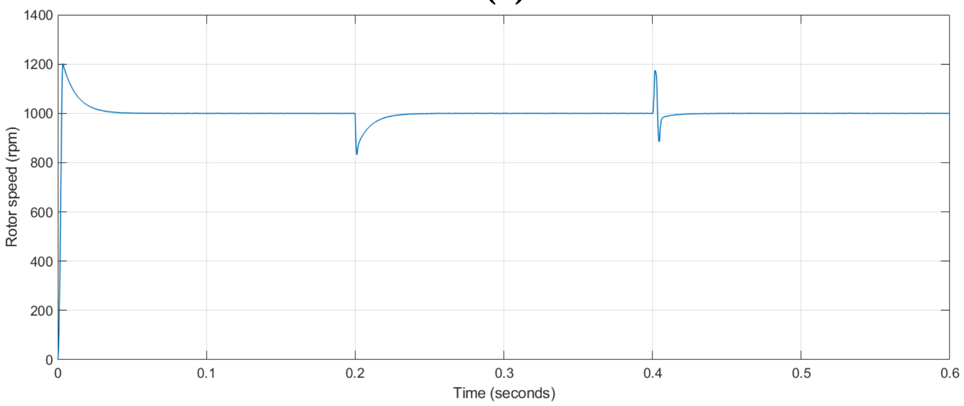


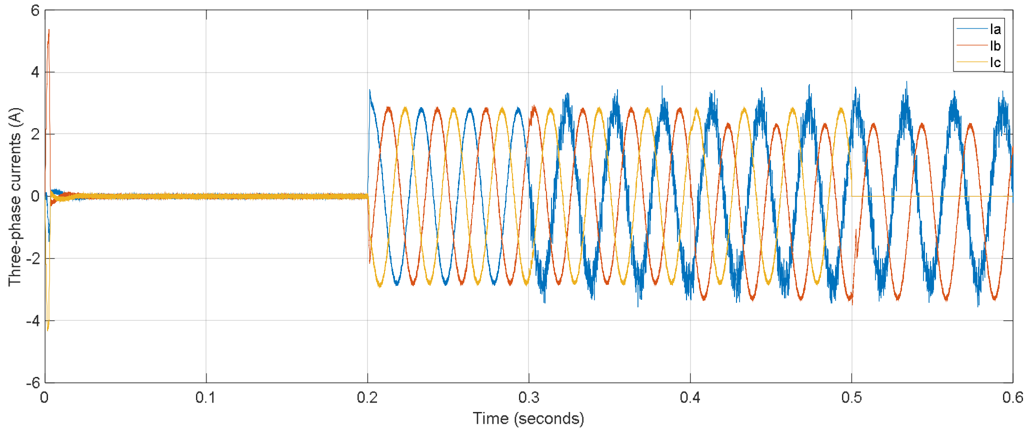
Fig.3.16 Simulation results of AFTC of SPMSM with saturation sensor a: (a) Measured abc currents (b) Estimated abc currents (c) Reconfigured abc currents (d) Measured d-q currents (e) Estimated d-q currents (f) Reconfigured d-q currents (g) Torque response (h) Speed response

Fig.3.16 illustrates the results of simulation for the proposed AFTC system that was applied on PMSM, the fault event in this test is the saturation in sensor a. After a short time (0.005sec) beyond t=0.4sec, The FDIR block reacts by giving an output signal Z=2 (in FDI block) replacing this faulty measured current by the correct current signal (in FR block) knowing that the current observer is not used in case of a single fault. To conclude, the PMSM is not affected by saturation in current sensors anymore.

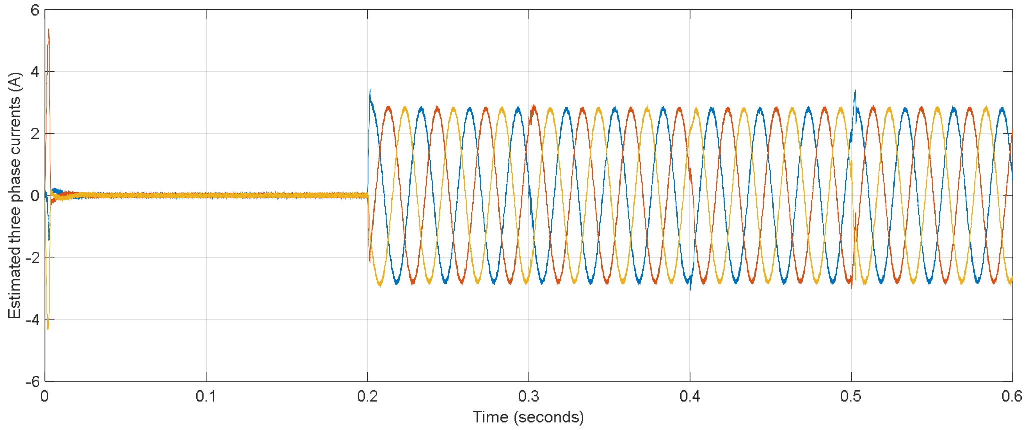
- **Multiple successive current sensor faults**

Three types of current sensor faults were treated. To test the proposed AFTC to other two faults, Combination of faults is conducted in order to see the effectiveness of AFTC against any type of faults. At t=0.3sec, current sensor a is having a noise fault. At t=0.4sec, sensor b is having negative DC-offset fault while at t=0.5sec sensor c is totally lost.

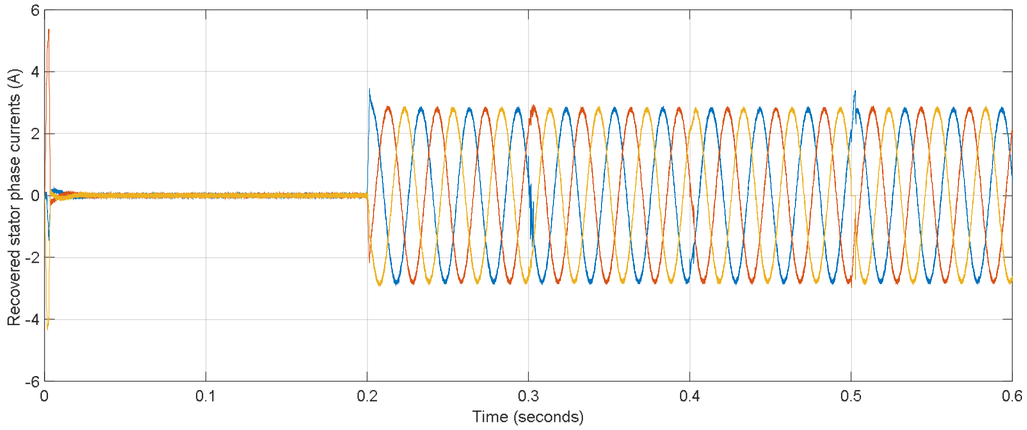
(a)



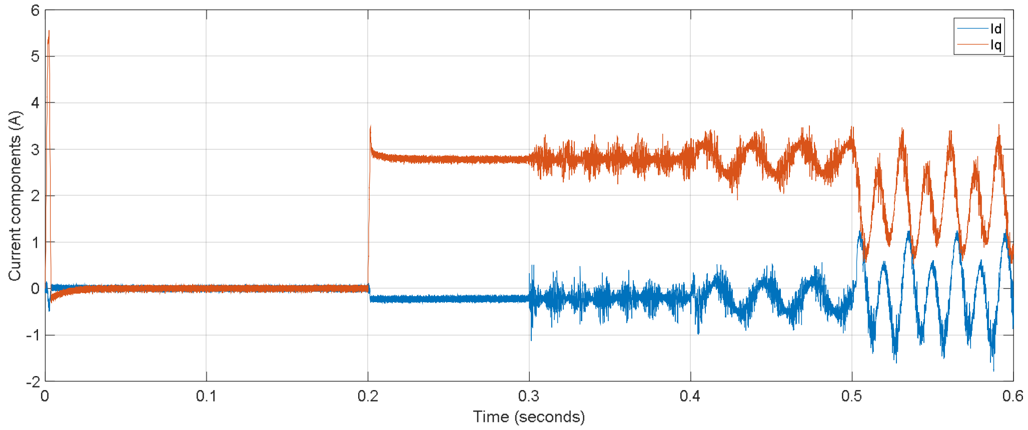
(b)


Estimated three phase currents (A)
6
4
2
0
-2
-4
-6
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

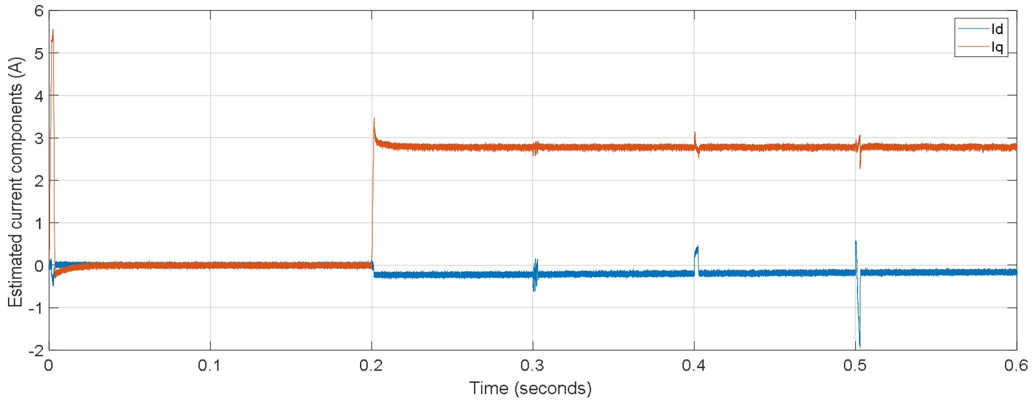
(c)


Recovered stator phase currents (A)
6
4
2
0
-2
-4
-6
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

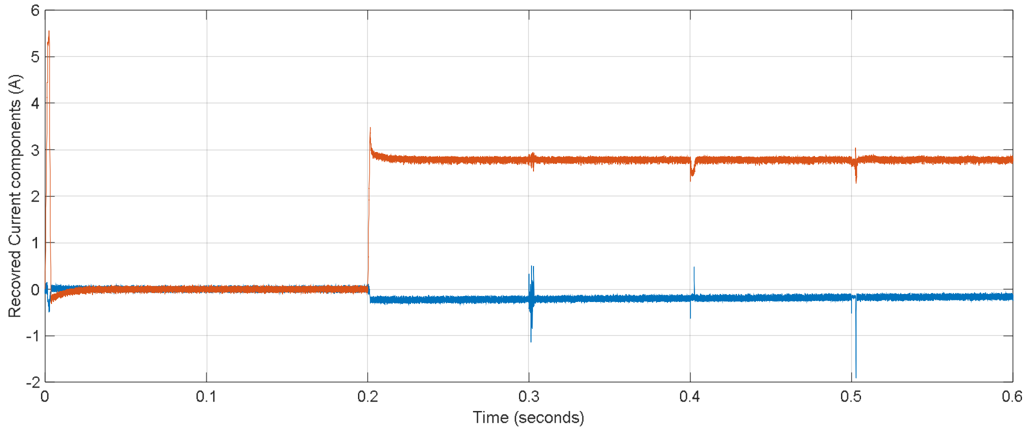
(d)


Current components (A)
Id
Iq
6
5
4
3
2
1
0
-1
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

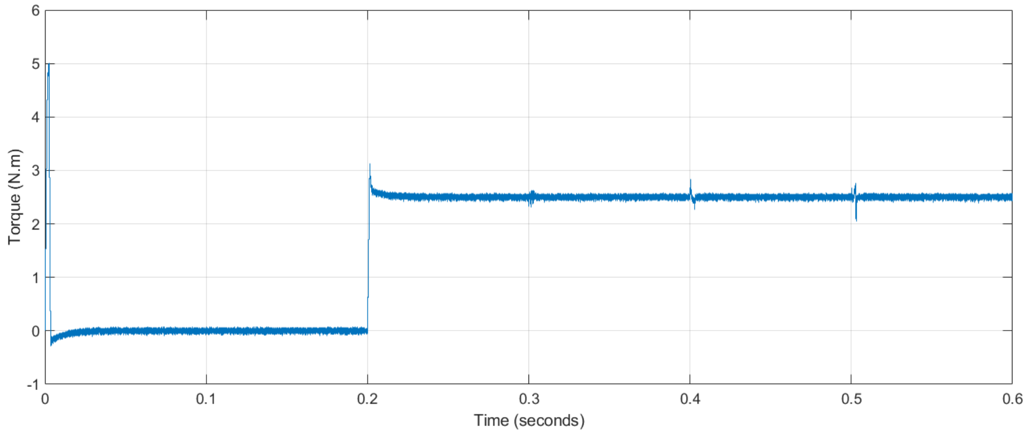
(e)


Estimated current components (A)
Id
Iq
6
5
4
3
2
1
0
-1
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
Time (seconds)

(f)



(g)



(h)

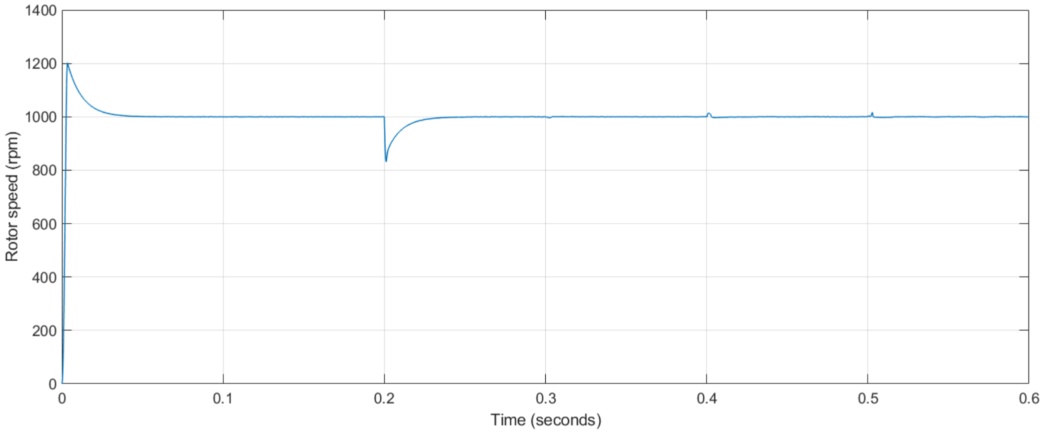


Fig.3.17 Simulation results of AFTC of SPMSM with multiple successive sensor faults: (a) Measured abc currents (b) Estimated abc currents (c) Reconfigured abc currents (d) Measured d-q currents (e) Estimated d-q currents (f) Reconfigured d-q currents (g) Torque response (h) Speed response

Fig.3.17 illustrates the results of simulation for the proposed AFTC system that was applied on PMSM, multiple successive faults were conducted. After a short time (0.005sec) beyond t=0.3sec, The FDIR block reacts by giving an output signal Z=2 (in FDI block) replacing this faulty measured current by the correct current signal (in FR block) knowing that the current observer is not used by the FDIR yet. After a short time beyond t=0.4sec, The FDIR block reacts by giving an output signal Z=5 replacing the two measured currents by the correct current signals by the use of current observer. At t=0.5sec, The FDIR block reacts by giving an output signal Z=8 replacing all measured currents by the correct current signals from the observer. Despite having successive and multiple failures in a small amount of time in all sensors, the PMSM's response to control commands as shown in the speed and torque responses is attractive.

3.7.2 Simulation results conclusion

AFTC proves its effectiveness to every type of current sensors failures in the PMSM drive by having a total control on these faults. The PMSM drive is current sensorless when using AFTC, It is achieved because of a good observer and efficient reconfiguration system. This property will increase the drive dependability and makes it unaffected to any kind of these faults.

After testing the effectiveness of the proposed AFTC system and simulating the whole system under several successive current sensor faults, one thing to be said is that the dependability of the PMSM drive system is high and consistent enough under current sensor faults when using this tolerant control type. Knowing that the dependability of a system incorporates RAMS attributes, The **Table3.3** summarizes and presents a simple comparison on the difference between non-tolerant and tolerant systems when undergoing current sensor faults (evaluation of the attributes only to current sensor faults).

Control systems / Dependab-ility attributes	Non-tolerant control systems.	PFTC systems.	AFTC systems.
Reliability	It is limited, when fault event the system will not be reliable anymore and needs to be repaired which depends on the	It is dependent to certain faults and the type of controller used. It can be increased by finding a balance between the robustness and performance when designing such	It is always achieved when system is having current sensor failures since the AFTC can operate in the sensorless mode as seen by the simulation results.

	redundancy used.	controllers.	
Availability	The system is only available when it is not undergoing current sensor faults. This kind of systems shut down directly when faults occur.	It is also dependent to certain faults and the type of controller used since PFTC is only efficient to certain faults. Thus, The system is available only when certain faults occur or when in normal state.	The system is always available whether undergoing current sensor faults or being in healthy state. The total availability can be increased by having other tolerant blocks to other types of drive faults.
Maintainability	It is dependent on the type of fault and maintenance used which makes system's continuity of service in danger.	Maintenance is of software type in this system and it is limited to certain faults. Maintainability of this system is attractive since faults were repaired in a very short duration but with a degradation in the system's performance.	Software maintenance is used and it is always present. Maintainability of this system is very attractive since faults were repaired in a very short duration with no degradation in performance.
Safety and security	It is dependent to the occurrence of faults.	It is dependent to certain faults and it is not attractive as system's continuity of service is achieved at the expense of some components.	The drive's environment is safe in the occurrence to any kind of current sensor faults and the best evidence is its sensorless mode of control.

Table3.3 Dependability attributes in multiple control systems

3.8 Chapter conclusion

In this chapter, passive and active fault tolerant techniques for current sensors have been proposed in the vector control of permanent magnet synchronous motor. Multiple current sensor faults were tested to see their effect on the drive's performance. The decrease in reliability, unavailability and unsecure service of electric drives under these faults necessitate a fault tolerant control system to limit their effects. In the passive tolerant system compensation between the robustness of the controller and the overall system performance must be treated. In opposite, the system's performance in the active tolerant system was consistent and continuous due to three important blocks. A detection algorithm with a circuit decision logic was applied for each phase, in order to identify faulty sensors. Immediately after the sensor failure, the FD block generates an output signal Z indicating failed sensors. Based on the values of Z, the reconfiguration block selects the correct current components by the use of a simple current observer allowing the continuity of service and uninterrupted operation. Several and successive current faults in the three sensors were simulated, The results showed the necessity for higher order SM controller in the PFTC systems and the ability of AFTCs to work on the current sensorless mode that increases the system's dependability and makes it unaffected to these faults.

General Conclusion and Perspective

During the last half-century, dependability and continuity of service were an obligation in a few fields such as telecommunications, transport and light industry, but essential in other fields such as aeronautics, defense, aerospace and nuclear. Today, the economic factor and operating safety standards play a very important role in all sectors which has opened the door to several avenues of scientific researches; among these researches we find the methods and concepts at the service of risk control. As a result, fault tolerant controls, which were a feature of some industries, have become essential for all industries.

This work discussed the fault-tolerant control of current sensors used in variable speed drives of three-phase permanent magnet synchronous motors. A study has been devoted to this subject, offering numerous solutions either for the detection of faulty sensors or for the reconstruction of currents. The solutions offered for the detection of faulty sensors are promising and diverse, on the other hand, the methods chosen for estimating and reconstructing stator currents are always limited to a few techniques which suffer from several drawbacks, such as the need to have at least one healthy current sensor, the need to restart the entire system in the event of recovery of a faulty sensor, the severe degradation of performance, etc.

The main objectives of this work are to design and test two fault tolerant control systems. The active tolerant control system is based on a single current observer which ensures the estimation of three-phase currents without the need of one healthy sensor associated with a fault detection and isolation mechanism, as well as the reconfiguration of the system for early and on-line detection of various defective sensors. Whereas the passive tolerant control system is based on a 1st order robust controller that under certain faults in expense of total system performance. Those methods were tested on Matlab/Simulink for an SPMSM.

The first chapter presented a state of the art on the main concepts, starting with a few definitions in the field of electric drives and dependability then fault tolerant control strategies based on software redundancy reviewing the various faults that may appear in the AC machine drives including PMSMs.

The second chapter presented an overview about PMSMs, the mathematical modeling based on simplifying assumptions and the multiple control techniques of PMSMs. The vector control (FOC-SVM) of PMSM was tested and simulated. The results were promising and can be considered as the image of a healthy electric drive system and are sufficient to be compared to results of an electric drive system under fault events which is done in the next chapter.

The fault tolerant control methods of current sensors proposed in this work are presented in the third chapter. It mainly dealt with the active and passive fault tolerant control of an SPMSM with current sensor faults in which there was a test about the effect of these faults on the system's continuity of service and security. Several simulation results of the FTCs of the SPMSM undergoing several successive current sensor faults were highlighted.

The PFTC proposed in this work is based on 1st order sliding mode when designing the speed controller. The aim of such system is to ensure the continuity of service under certain faults by the expense of performance degradation. What remains in designing a SM speed controller in PMSMs is to find balance between the robustness of the controller and the chattering side effect for wide range of operating conditions. In other words, having a good robustness to several current sensor faults while having constant performance. To improve the design of such controllers, 2nd order SM could be used. The PFTC of certain current sensor faults is attractive in some domains due its simplicity in design and efficiency under these faults. It could also be unattractive in other domains due to its side effects and its fault type dependent design.

The AFTC proposed in this work is divided into two parts, the FDIR part which ensures the detection and isolation of faults as well as the reconfiguration of the system and the part which ensures the reconstruction of the stator currents. In order to ensure the detection, isolation and reconfiguration of the electrical drive system in the event of a current sensor fault, a decision circuit has been put in place. Current sensors are located on the stator phases of the machine to detect any unusual and undesirable change in the signals of the measured quantities due to a gain fault, an offset fault or a total break in the sensor signal, the error between the measured currents and the estimated currents is calculated at each sampling step. The absolute values of the error obtained on each phase are always kept under analysis by a logical comparator regarding a threshold. Consequently, in the event of a fault on one or more sensors, the output of the logic comparator corresponding to the faulty sensor is set to the value 1. After the detection of the faulty sensor, then comes the isolation, where according to the outputs of the three logic comparators a decision is made to isolate the sensor(s) and replace the erroneous measurement(s) by a correct estimate. Certainly, this method is simple and effective; on the other hand, it is always limited because it requires the selection of an appropriate and well-defined threshold for each system.

Successful active fault tolerant control of high-performance current sensors is synonymous with good reconstruction of currents. Until now, little work has offered a solution for the reconstruction of three-phase currents based on a single estimator without resorting to current sensors. The method proposed in this work for the estimation of the PMSM stator currents ensures this task even in the event of failure of all the current sensors which makes the drive system unaffected to any current sensor fault.

Needless to say, the subject in question is far from being exhausted and the work of this work has opened up other avenues for improvement. The plan for the continuity of the work in the short term aims to:

- Implementation of the work carried in this work.
- Apply the AFTC method on a traction chain of an electric vehicle and an autonomous photovoltaic pumping system.
- Develop an artificial intelligence-based fault detection and isolation method that can detect faults in current sensors by skipping the trip threshold adjustment phase.
- Study the effect of the machine faults and parameters on the current estimator.
- Extend the tolerant control over the entire control system including machine faults.
- Developing the sensorless control of the system using MRAS for speed estimation.
- Developing the blocks used in both tolerant systems like using a super twisting 2nd order sliding mode controller in the PFTCs.
- Developing the PFTCs to tolerate under all current sensor faults.
- Expansion of the FDIR block to the FDIIR where fault identification is present and developing identification techniques to avoid the famous overlapping phenomena.

Appendices

Appendix A.1: PI speed controller's gains calculation

The used PI controller in the outer speed loop for all control schemes is the anti- windup controller. The dynamic equation and the transfer function using Laplace transform of the speed loop are given as following:

$$\frac{d\omega_r}{dt} = -\frac{f}{J}\omega_r + \frac{T_e}{J} - \frac{1}{J}T_L \tag{A.1}$$

$$G\omega_r(s) = -\frac{\omega_r(s)}{T_e(s) - T_L(s)} = \frac{\mathbf{1}}{\boldsymbol{Js - f}} \tag{A.2}$$

The transfer function (TF) of the PI controller is defined as follow:

$$PI = K_p - \frac{K_i}{s} \tag{A.3}$$

K_p and K_i are the proportional and integral gains.

s is Laplace operator.

Then, **Fig.A.1**. shows the block diagram of the speed control loop.

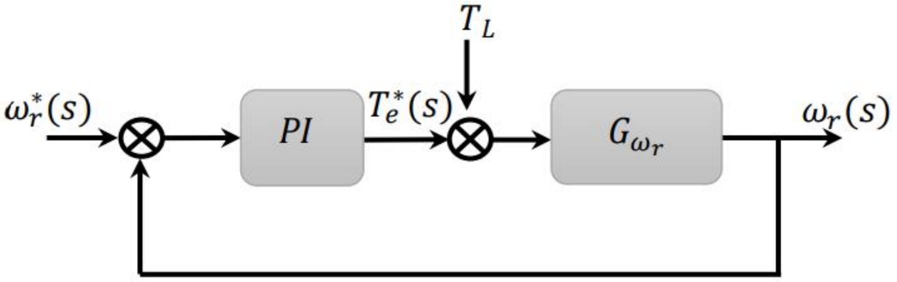


Fig.A.1 Speed control loop

By considering the load torque T_L as a disturbance. The global transfer function of the speed control in open loop becomes:

$$G\omega_r(s) = \frac{\omega_r(s)}{\omega_r{}^*(s)} = \frac{1}{Js+f}\left(K_p s + \frac{K_i}{s}\right) \tag{A.2}$$

In closed loop, the TF becomes

$$G\omega_r(s) = \frac{K_P s + K_i}{Js^2 + (K_P + f)s + K_i} \tag{A.3}$$

By identification member to member, the denominator of the equations (A.31) with the canonical form of second order system given in (A.32):

$$G(s) = \frac{1}{s^2+2\xi\,\omega_n s+\omega_n{}^2} \qquad \text{(A.4)}$$

where ω_n is the natural frequency and ξ is the damping coefficient.

we obtain:

$$\begin{cases} \frac{J}{K_i} = \frac{1}{\omega_n{}^2} \\ \frac{K_P+f}{J} = 2\xi\omega_n \end{cases} \qquad \text{(A.4)}$$

The gains are determined for a damping coefficient $\xi = 1$.

Appendix B:

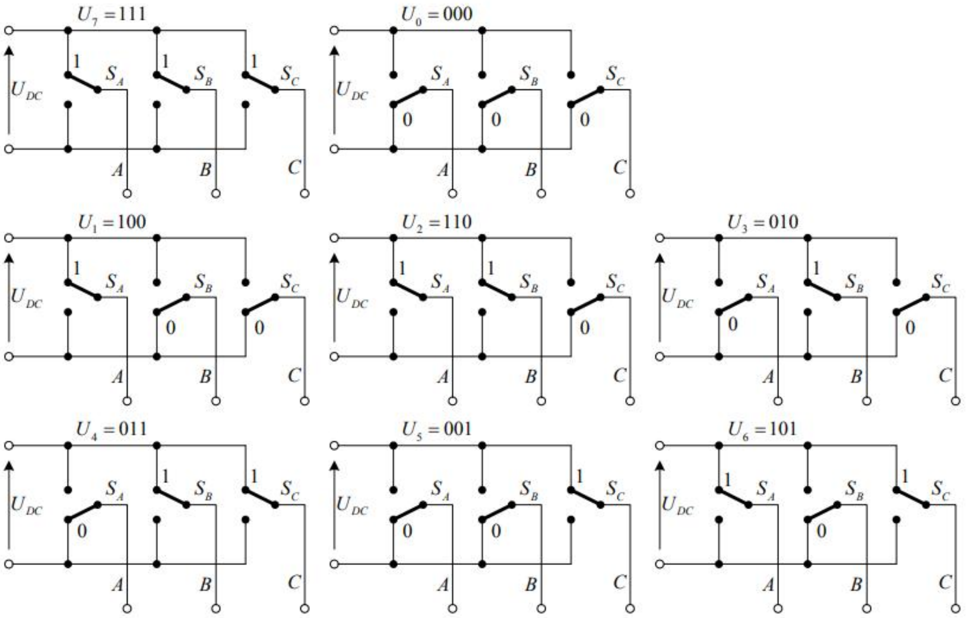


Fig.B.1 Possible switches state in VSI

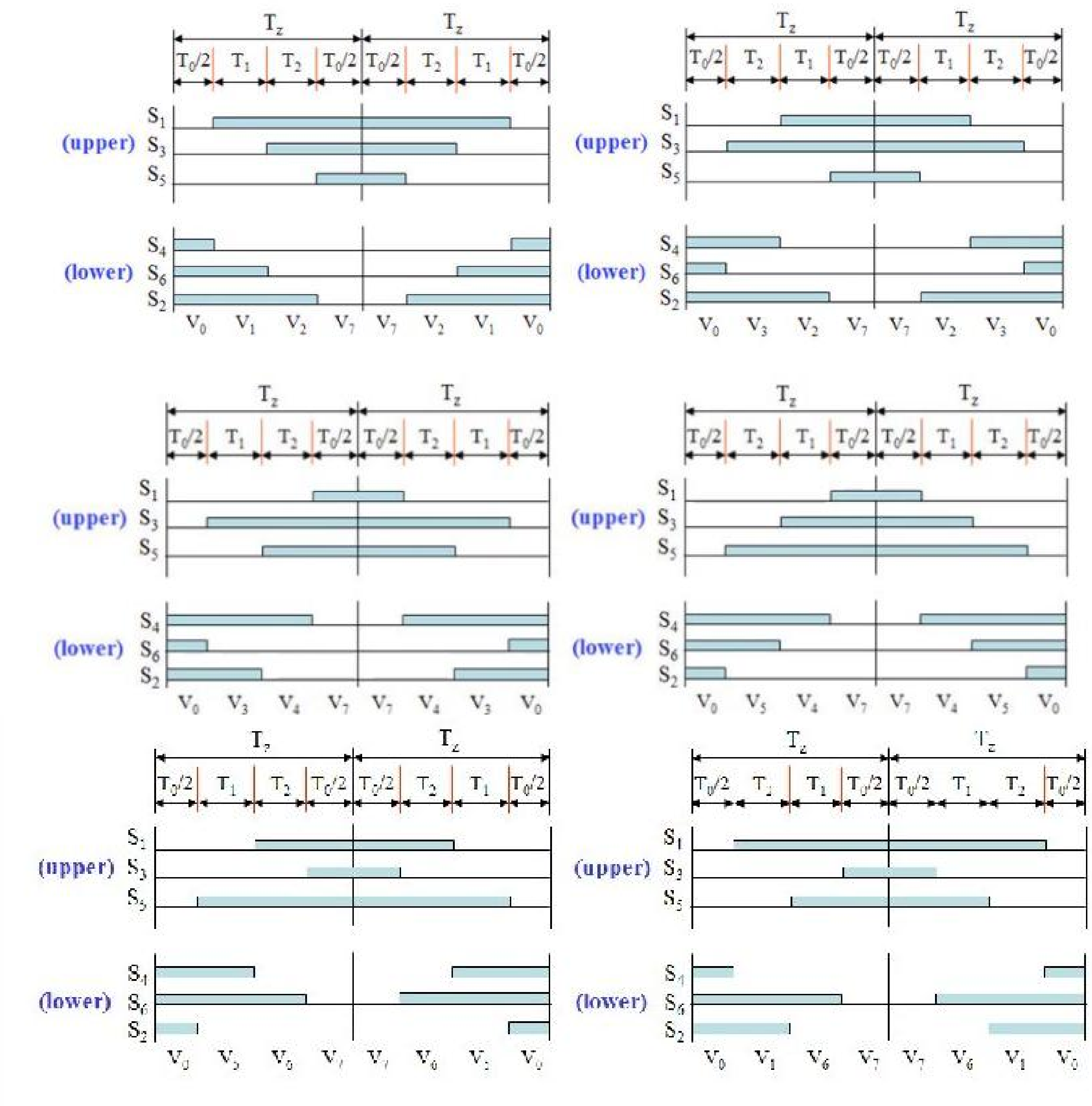


Fig.B.2 Switching times for each sector in SVPWM technique

Specifications		Parameters	
Nominal power [W]	415	R_s = [Ω]	4
Nominal voltage [V]	53	L_d = [mH]	43
Nominal current [A]	4.5	L_q = [mH]	43
Number of pole pairs	2	ψ_r = [Wb]	0.3
Nominal speed [rpm]	1500	J = [Kg.m2]	85e-6
Nominal torque [N.m]	2.6	F = [Nm.s.rad^{-1}]	0.000005

Table.B.1 SPMSM parameters

Appendix C: Robust control design

There are various methods in literature for control design. The most common of them are the relay control, the equivalent control scheme and the linear feedback with switched gains. The equivalent control is the most used structure for the control of electrical machines (Fig.C.1). It is preferred due to the relay control which is more suitable for the structure of the power electronics converters.

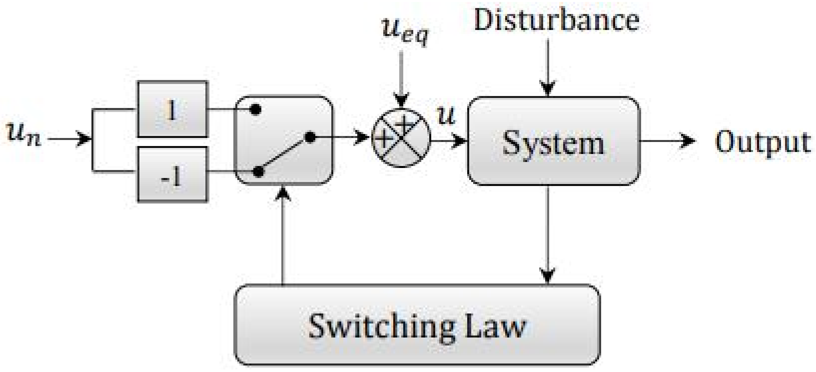


Fig.C.1 Equivalent control structure

The design of sliding mode control is mostly performed by two parts. The equivalent control u_{eq} is added to another control term called the discontinuous control u_n in order to ensure that the state trajectory reaches and stays on the switching surface.

The control law expression is given by:

$$u = u_{eq} + u_n \tag{C.1}$$

By considering the following state system:

$$x = A(x)^{\cdot} + B(x)u \tag{C.2}$$

The equivalent control is found by recognizing that $\dot{S} = 0$ is a necessary condition for the state trajectory to stay on the switching surface S=0.

The time derivative of the sliding surface is given as:

$$\dot{S} = \frac{\partial S}{\partial t} = \frac{\partial S}{\partial x}\frac{\partial x}{\partial t} \tag{C.3}$$

By substituting (C.1) and (C.3) into Eq (C.2):

$$\dot{S} = \frac{\partial S}{\partial x}A(x) + \frac{\partial S}{\partial x}B(x)u_{eq} + \frac{\partial S}{\partial x}B(x)u_n \tag{C.4}$$

The equivalent control is defined during the sliding phase and the steady state where $S = \dot{S} = 0$ and u_n=0.

$$u_{eq} = -\left(\frac{\partial S}{\partial x}B(x)\right)^{-1} = \frac{\partial S}{\partial x}A(x) \tag{C.5}$$

The existence of an inverse matrix is a necessary, which means the next condition (C.6):

$$\frac{\partial S}{\partial x}B(x) \neq 0 \tag{C.6}$$

By substituting (C.5) in Eq (C.4), the new sliding surface expression becomes:

$$\dot{S} = \frac{\partial S}{\partial x}B(x)u_n \tag{C.7}$$

The discontinuous control un is determined during the convergence state and must guarantee the finite time convergence condition $S\dot{S} < 0$ which is given by:

$$S\dot{S} = S\frac{\partial S}{\partial x}B(x)u_n < 0 \tag{C.8}$$

In order to satisfy this condition, the sign of u_n must be the opposite of the sign of $S\frac{\partial S}{\partial x}B(x)$. The discontinuous control is defined as a switching term formed by relay function $sign(\mathrm{S})$ multiplied by a constant coefficient *K*.

The relay function is defined by:

$$sign(\mathrm{S}) = \begin{cases} +1 & if \;\; S \geq 0 \\ -1 & if \;\; S < 0 \end{cases} \tag{C.9}$$

$$u_n = -K\, sign(\mathrm{S}) \tag{C.10}$$

The coefficient *K* must be positive to ensure the convergence condition.

In order to limit the effect of chattering, the “sign(S)” will be replaced by sigmoid function “sigm(S)”.

$$sigm(\mathrm{S}) = \left(\frac{2}{1+\mathrm{e}^{q\mathrm{S}}}\right) - 1 \tag{C.11}$$

q is a small positive constant which adjusts the sigmoid function slope.

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