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Option: **Power Engineering**

Title:

Open Switch Fault Detection and Localization of a Three-Phase Permanent Magnet Synchronous Machine Using Fuzzy Logic

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Registration Number: ……. /2023

Dedication

I dedicate this thesis to my beloved father and mother and my two sisters who showed me their kind words and encouragement to finish this study and to the real friends who I had the chance to meet and love, and to each and every person who shared his words, I am eternally grateful for the values and principles you have instilled in me, which have guided me towards this achievement. This thesis is a tribute to your unwavering faith in me.

[Khaled Mohamed Amine]

Dedication

To my precious Mother

To my beloved Father

To my dear brothers and sisters

To my niece (YASMINE)

To every person wishing me every success

To my partner in this work: Khaled Mohamed amine

And again, to my teachers of all levels. I dedicate this work

[*DECHIR OUSSAMA*]

Acknowledgment

First of all, all gratitude to Allah for providing the strength and blessing needed to complete this job, also we would like to offer our heartfelt appreciation to Our project supervisor, **Dr. AMMAR Abdel Karim**, Finally, we are eternally thankful to our family members, especially our parents, for their prayers, wisdom, and support during our schooling. Their motivation and support have been essential, I would like to express my sincere gratitude and appreciation to the **IGEE** family which give us the opportunity to gain technical knowledge, soft skills and funding.

[Khaled Mohamed Amine, Dechir Oussama]

Abstract

Power electronic systems are considered as one of the most critical components in many applications, such as nuclear reactors. In such cases, the system must be extremely reliable like Permanent Magnet Synchronous Motors (PMSMs).

The report begins with an overview of PMSM types and variable frequency drives followed by proofreader explanation of faults that may occur in this type of motors .The modeling of PMSM is the work's core contribution. Starting first with a sufficient investigation into the steady-state and dynamic properties of PMSM in both stationary and rotating frames, followed by a discussion of switching states in a three-phase inverter along with Space vector pulse width modulation, Furthermore, in order to attain higher dynamic performance, a more advanced control method known as field oriented control (FOC) must be utilized to regulate the PM motor.

At the last part of the report, fault diagnostic and detection of our motor is controlled using fuzzy logic approach, and promising results were obtained in simulation on MATLAB/Simulink.

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List of Abbreviations

AC	Alternative Current
BLDC	Brushless Direct Current
DC	Direct Current
DE	Dynamic Eccentricity
DSP	Digital Signal Processing
DTC	Direct Torque Control
EMF	Electromagnetic Torque
FDD	Fault Detection and Diagnosis
FOC	Field Oriented Control
FTC	Fault Tolerance Control
FTCS	Fault Tolerance Control System
IGBT	Insulated Gate Bipolar Transistor
ME	Mixed Eccentricity
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
SE	Static Eccentricity
SPMSM	Surface Mounted Permanent Magnet Synchronous Motor
SVM	Space Vector Modulation
V/F	Voltage/Frequency
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
VSI	Voltage Source Inverter

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General Introduction

General Introduction

Overview:

Permanent magnet synchronous motors (PMSM) are commonly utilized for high performance and efficiency applications. High-performance motor control is distinguished by smooth spinning across the motor's speed range, full torque control at zero speed, and rapid acceleration and deceleration. Vector control techniques are employed for PM synchronous motors to accomplish such control. The vector control method works by decomposing a stator current into a magnetic field-generating component and a torque-generating part. Following breakdown, both components may be controlled independently. The structure of the motor controller (vector control controller) is therefore nearly identical to that of a separately excited DC motor, which simplifies the management of a permanent magnet.

In order to achieve the desired performances of PMSMs as the behavior of DC motors, direct control of stator currents is needed. Nevertheless, it is quite unattainable due to the strong coupling and nonlinear natures of the AC motors. Hence, to realize the decoupling of relevant variables, a particular algorithm must be introduced. Fortunately, this problem has been resolved by the vector control technology, often referred to as Field-Oriented-Control (FOC), which gives improved performance in terms of faster dynamic response and more efficient operation.

A fault is an unauthorized deviation of at least one system characteristic property or parameter from the standard condition. Three main types of faults can be indicated in the case of drive systems: motor faults, power converter faults, and sensor faults. starting with power electronics faults, which can be divided into power semiconductor faults and DC bus faults, another type of failure are mechanical faults and electrical faults concerning the motor. The last type are sensors faults,

Which may concern mechanical or electrical variables. 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.

Faults in automated processes will often cause undesired reactions and shut-down of controlled plant, and the consequences could be damage to the plant, to personnel or the environment. Fault-tolerant control is the synonym for a set of recent techniques that were developed to increase plant availability and reduce the risk of safety hazards. Its aim is to prevent that simple faults develop into serious failure. Fault-tolerant control merges several disciplines to achieve this goal, including on-line fault diagnosis, automatic condition assessment and calculation of remedial actions when a fault is detected.

Fault Tolerant Control (FTC) was created over 20 years ago, along with Fault Detection and Diagnosis (FDD) approaches. The FTC seeks to maintain system functionality even when a failure occurs. FTC systems can detect component failures automatically by employing appropriate FDD methodologies. As long as the controlled system can be safely stopped for maintenance or repair, they can retain overall system stability and appropriate performance. In other terms, a Fault Tolerant Control System (FTC) is a closed-loop control system that can tolerate component faults while preserving desirable performance and stability attributes.

Aims of this thesis

The main objective of this thesis is the open-switch voltage source inverter fault tolerant control (FTC) for DTC-controlled induction motor. This work addresses two principal points. The first point is the design of PMSM drive controlled by FOC (Field Oriented control) using a six-switch three-phase inverter (SSTPI). By completing the first point, we will move to the second point, which is the detection and diagnosis of online multiple open-circuit faults in the voltage source inverter used in the FOC of the drive system using fuzzy logic approach.

Organization of the thesis

Following the general introduction, which provides an overview of the main points that will be discussed in this thesis, the thesis' main body is organized as follows: The first chapter provides an overview on Permanente Magnet Synchronous Motor and its characteristic and its advantages over other motor, after that we discuss the characteristic of different PMSM motor control strategies. Then, we will be discussing the different induction motor drive system faults, as well as the fault tolerant control strategy.

The second chapter presents the field oriented control of PMSM drive using a six-switch three-phase inverter (SSTPI). Simulation results are presented.

The third chapter deals with multiple open-switch fault diagnosis and detection using fuzzy logic approach. Also, simulation results are presented.

Chapter 1

Overview on VFD & FTC

Introduction

The permanent-magnet synchronous motor (PMSM) has been widely used in the industry for variable speed applications due to its high performance reliability and power density. Owing to the progress in the permanent magnet materials, micro and power electronics, fast digital signal processors, and modern control technologies, permanent magnet synchronous machines have become more widespread in industrial applications, such as in automobiles, robotics, aeronautics, and aerospace domains.

Greater motor control can be achieved with the help of variable frequency drives (VFDs), which can offer smoother speed tuning. Over the years, numerous AC drive control systems have been created in order to regulate the torque, speed, and position. Based on their underlying concepts, they can be divided into two categories: scalar control methods and vector control methods. The scalar control is developed using the machine’s steady state model (per phase equivalent circuit model), which can only control the magnitude and frequency of voltage, current, and flux [1]. As a result, during the transient state, it does not operate on the space vector position. In contrast, vector control is developed in dynamic states; more than the magnitudes, the instantaneous positions of voltage, current, and flux can be controlled [2].

Due to their high power density and efficiency, high torque to volume ratio, excellent dynamic performance, simple and compact structure compared to induction or reluctance motors, PMSM have garnered a lot of attention among other electrical machine in the last twenty years in robotic and traction vehicles [3]. However, PMSM, like other electrical machines, are susceptible to various damages on an electrical (stator winding), magnetic (PM), and mechanical (bearings, unbalance, eccentricity) nature caused by various stresses that occur during long operation in severe conditions [4]. A notably important and contemporary challenge is the detection, identification, and isolation or tolerance of these damages in their first stage due the increased usage of PMSM in devices of critical nature, such as transportation application and wind power production [5], [6]. Manufacturers of control systems for AC drives are becoming more and more interested in integrating diagnostic features into their converter control algorithms as a result of consumers increasing demands for the reliability and safety of installed drives. The present advancements in sensor technology, measurement tools, digital signal processing software, and computational intelligence allow for continual drive status monitoring and observation of trends.

This allows the detection of failures occurring at their initial stage and the prognosis of the drive system [7]-[8].

Permanent Magnet Synchronous Motor

The permanent magnet synchronous motor (PMSM) is an AC synchronous motor whose field excitation is provided by permanent magnet, the PMSM is a cross between an induction motor and brushless DC motor.

The most important characteristics of the PMSM will be introduced in the following section [9].

1.1 Classification of permanent magnet synchronous motor

The physical characteristics of the PMSM are associated with its rotor and stator structures.

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.

The **Rotor** incorporates permanent magnets 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.

On the other hand, there exist several ways to place the magnets in the rotor (see Fig.1.1).

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

- **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. The inductances do not depend on the rotor position (Fig. a). The inductance of the axe-d is equal to those of the axe-q. 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.

- **Inset magnets type**

The inset magnets are placed on the surface of the rotor. However, the space between the magnets is filled with iron (see Fig. 1.3b). 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.

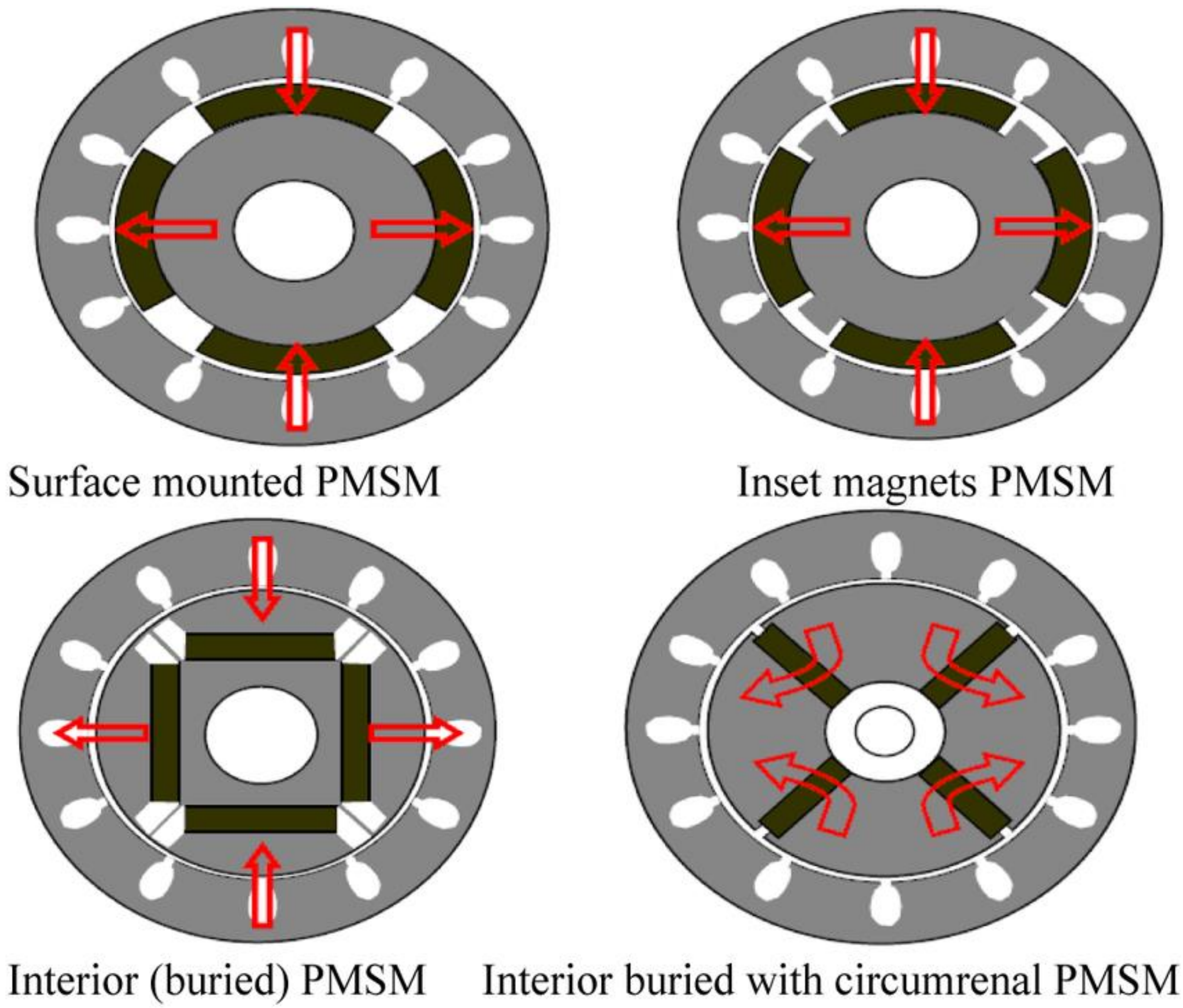


Figure.1.1 PMSM rotor permanent magnets

- **Interior magnets type**

The magnets are integrated in the rotor's body (Fig. 1.3c): 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 in 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.

- **Flux concentrating type**

As shown in Fig. 1.1d, 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 [9].

1.2 Advantages and disadvantages of PMSM

Modern permanent magnet synchronous motors can be operated close to unity power factor and have a large pull-out torque for a given frame size[10]. PMSM does not provide rotor side excitation control. Control is done entirely via the stator terminals. In low power application, field excitation can be provided using permanent magnet, eliminating the need for field winding losses, DC sources, brushes, and slip rings 11].

– Advantages of PMSM over induction motor

The PMSM is more suitable than the induction motor because of the synchronous machine's intriguing benefits, which include [12].

- Higher efficiency and more reliable and less noisy.
- Higher power density and higher power factor with ability to maintain full torque at low speed.
- 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.

– Advantages of PMSMs over BLDCs

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 [12]: 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

Table1.1 tha main differences between electric motors.

	DC motor		AC motor		
	Brushless DC motor	Brush DC motor	Induction motor	PMSM	Synchronous motor
Efficiency (%)	85-95	75-85	80-90	85-95	85-95
Starting torque (N.m)	high	Moderate	Low to moderate	High	high
Speed range (rpm)	100-10000+	1000-10000	900-3600	100-10000+	900-3600
Rated power (kW)	0.1-100	0.1-10	0.1-100	0.1-100	0.1-100
Maintenance	low	high	low	low	low
Control complexity	Moderate	Low	Moderate to high	Moderate to high	Moderate to high

Cost	Expensive	Low to moderate	Low to moderate	Expensive	Moderate to high
Application	– Robotics – Electric vehicle – Industrial automotion	– Household appliances – Automotive accessories – Medical equipments	– Industrial pumps and fans – Oil and Gas industry	– Electric and hybrid vehicle – Industrial machine and robotics	– Power factor correction – Some HVAC systems

Variable frequency drive

1.3 Scalar control

1.3.1 Volt/Frequency scalar control

Scalar control (frequency control) is brushless AC motor control technique intended to keep the voltage-to-frequency ratio (V/Hz) constant over the entire operating speed range by controlling only the magnitude and frequency of the supply voltage [13].

1.3.2 Open loop V/F method control

This method is very popular in term of speed control. Because of their simplicity, these motors are widely used in industry. The advantages of this type of motor include low cost, ease of operation and feedback signal immunity [14].

For a constant speed applications, a motor with a 50Hz open loop power supply was most likely used. The variable controlled in this process are synchronous speed and stator frequency, but synchronous speed is slightly higher than rotor speed, making motor speed control impossible. The stator current thus clearly exceeds the nominal current. The variation of the synchronous speed Ns and the rotor speed poses a problem as it makes it difficult to maintain the slip speed [15].

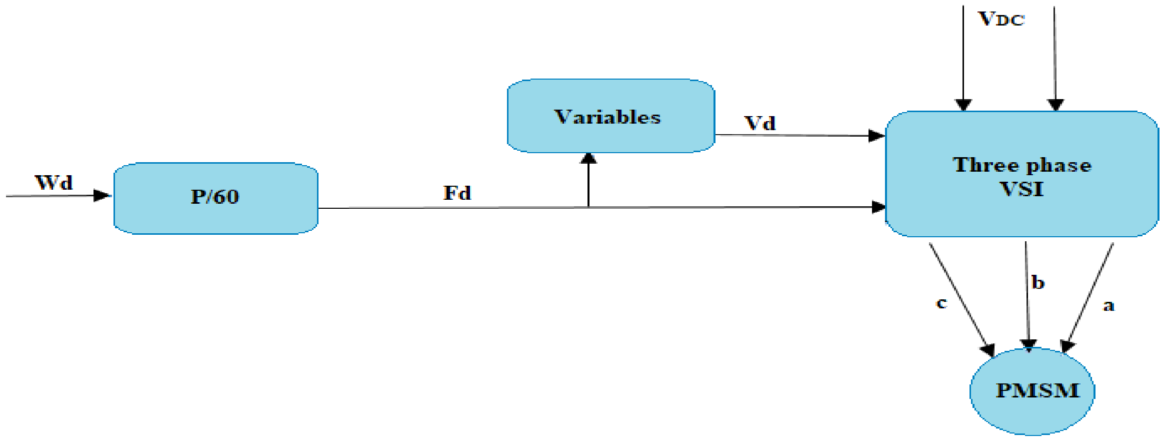


Figure.1.2: open-loop scalar control of three phase VFD

Where **Wd:** desired rotor speed, **P:** number of pole pairs, **Fd**: desired frequency

1.3.3 Closed loop V/F method control

To control the speed in a closed loop, proportional-integral is used to keep the speed at a desired value and improve speed accuracy by regulating the slip speed of the motor. The controller receives the speed tracking error, which is the difference between the desired reference Wr* and the actual sensed rotor speed Wr as described in figure below [14].

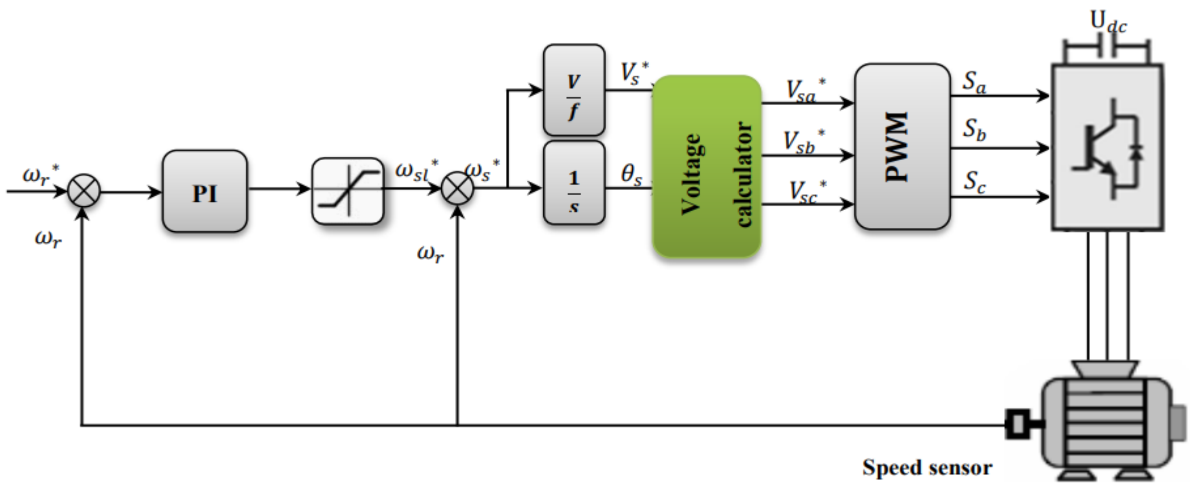


Figure.1.3 closed loop scalar control of three phase VFD

1.4 Vector control

1.4.1 Field Oriented Control

To achieve better dynamic performance, more complex control scheme should be adopted to control PM motor. With the mathematical processing power provides by the microcontroller, advanced control strategies can be implemented using mathematical transformation to control both AC and DC machines, providing the ability to independent control of the generated current and torque. Such decoupled torque control and magnetization is commonly referred to as FOC [16].

1.4.1.1 The Main Philosophy behind the FOC

Start with a description of the individually excited (DC) motor in order to comprehend the FOC technique's philosophy. Torque is defined as the cross product of armature current and stator flux. Electrical research of DC motor shows that armature current and stator flux can be independent such an example. The excitation intensity of the field (magnitude of field excitation current) determine stator flux value. If the magnetic flux is kept constant, the current through the rotor has a role of interesting part of the torque production. The commutator is in contact with the brush, and mechanical structure designed to incorporate coils that are mechanically aligned to produce maximum torque. This provision means the machine's torque output is almost always optimal. The key point here is that the winding are managed to maintain the magnetic flux generated by the winding of the orthogonal rotor coming from the stator magnetic field/current.

The essential characteristics of AC machines differ from those of a DC motor. The flux and torque producing current are not necessarily orthogonal. In PM synchronous machines, the permanent magnets installed on the shaft provide the rotor excitation, and the stator carries the current that generates the torque. In induction machines, the stator carries both flux-producing and torque-producing currents, and its only source of energy is the stator phase voltage. The flux and torque component that produce the current are tightly connected in contrast to a DC machine.

To be able to operate synchronous and asynchronous machines like a separately excited DC machine, where the flux producing and torque producing currents are independently regulated, is the aim of FOC (also known as vector control) on those machine. To put in another way, the aim of the control technique is to somewhat resemble the control of DC motor. We shall be able to control the flux and torque producing currents separately thanks to FOC control. The use of numerous mathematical transforms is required to decouple the currents that produce torque and flux, and here is where microcontroller are most useful. Because of the microcontrollers processing power. These mathematical adjustment can be completed very.

This suggests that the full motor control algorithm can be run fast, resulting in improved dynamic performance. In addition to decoupling, numerous parameters, including rotor flux angle and rotor speed, are now computed using dynamic model of the motor. This indicates that their impact is taken into consideration, and the overall standard of control is higher.

In the dq reference, a three phase PM machine can be represented as a DC machine. Where the d-axis aligns along the rotor's flux and the q-axis is perpendicular to the d-axis. Any current running flowing along the d-axis, can affect the strength of the magnetic field and the current on the q-axis will interact with the magnetic flux on the d-axis to produce a torque.

In short, for PM motor, the goal is to keep the current on the d-axis to zero and adjust the magnitude of the current on the q-axis to produce the required torque. The positive-sequence component of the stator current can be kept negative in some cases to weaken the magnetic field, which has the effect of reducing the rotor flux and reducing reverse EMF, thus allowing operation at higher speed [16].

1.4.1.2 Technical background on FOC

The FOC effectively controls the stator current vector. This control is based on projections that transform a time-varying three phase system into time-invariant system with two coordinates (d and q coordinate). These projections result in a structure similar to that of a DC machine controller. The field oriented controller needs two constants as input references: the torque component (aligned with the q coordinate) and the magnetic flux component (aligned with the d coordinate). Since the FOC is simply based on projections. The control structure manage the instantaneous power. This make the control precise in every working operation (steady state and transient) and does not depend on the limited bandwidth mathematical model [16].

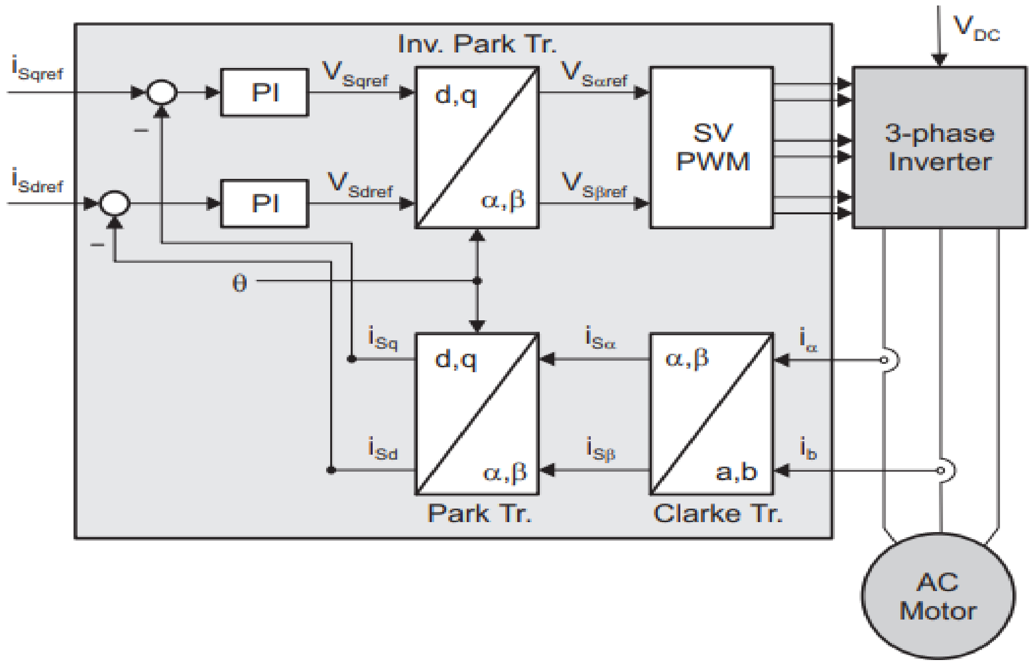


Figure 1.4: basic scheme of FOC for AC motor

1.4.2 Direct Torque Control (DTC)

The fundamental idea of DTC (Direct Torque Control) is to choose the stator voltage vector based on the difference between reference values and actual torque and stator flux linkage value. DTC is superior to Field Oriented Control (FOC). Uses no current controller and only the stator resistance as a motor parameter. Provides various benefits, including less dependence on machine parameter, easier implantation, and fast dynamic response to torque. The sensorless operation of the PMSM under DTC is possible if the initial position of the rotor is known approximately [17].

It main features are as follow [18]:

- Direct torque control and direct stator flux control.
- Indirect control of stator currents and voltages.
- Approximately sinusoidal stator fluxes and stator currents.
- High dynamic performance even at locked rotor.

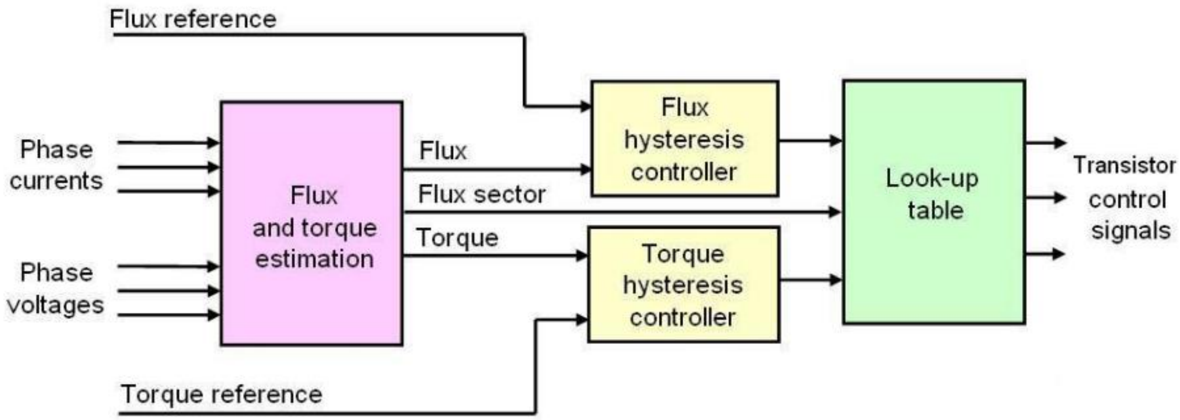


Figure.1.5: basic scheme for DTC

Fault Tolerance Control

1.5 PMSM drive fault

1.5.1 PMSM fault classification

There are several distinct types of PMSM failures. They are separated according to their type into electrical, magnetic, and mechanical damages [19], [20]. However magnetic damage can be attributed in mechanical damages [21]. In turn, PMSM faults are classified by location, as stator related failures (related to the winding and core) and rotor related failures (demagnetization, eccentricity, and imbalance) [22]. The classification of PMSM fault are shown in figure 1.6, according to which they will be analyzed.

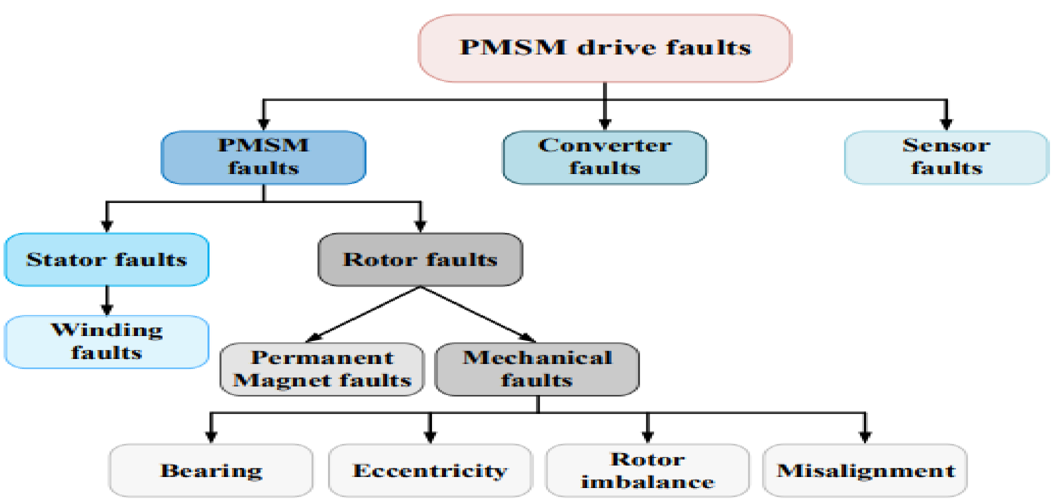


Figure.1.6: fault classification of PMSM drive.

1.5.2 Motor related fault

1.5.2.1 Stator winding faults

- **Inter turn short circuit**

  ITSC have a particularly harmful character as they are spreading out extremely fast. Stator winding problem frequently start as an unnoticeable ITSC then expand to the entire winding .ITSC are mainly caused by the insulation deterioration [23].

- **Insulation deterioration**

  The major causes of stator winding insulation problem are excessive temperature and overloading. Winding insulation problems can lead to changes in torque, unbalance, current harmonics, overheating, and vibration. Without timely identification and rectification effort, it can rapidly propagate to further stator windings turns and then may cause demagnetization, power loss or damage of PMSM [24].

1.5.2.2 Rotor faults

- Permanent magnet fault

  Demagnetization is a unique feature of PMSMs and concerns permanent magnets. The damages may be mechanical in nature or related to the phenomenon of demagnetization[4].the magnet's demagnetization may be partial across a specific region or pole or uniform over all the poles.PM could be demagnetize for a variety of reasons, including : high operation temperature /cooling system malfunction, corrosion of magnet, aging of magnets and inappropriate armature current[25].

- **Mechanical faults**

- **Bearing fault**

Most electrical machines use ball or rolling bearings. Each bearing consist of two rings, one inner and one outer. A series of balls or rolling elements arranged in raceways rotate within these rings [26]. Even under normal operating conditions with balanced load and good alignment, fatigue failures may take place. Flaking or spilling of bearings might occur when fatigue causes small pieces to break loose from the bearing. Apart from normal internal operating stresses, other causes of bearing damages due to vibration, inherent eccentricity, and bearing currents appear as well[25].

- **Eccentricity fault**

Eccentricity occurs when air gap between the stator and rotor becomes unequal. Static eccentricity (SE), dynamic eccentricity (DE), and mixed eccentricity (ME) are the three types of eccentricity faults. They develop as a result of production faults such imbalanced mass, shaft bow, and bearing tolerance. Eccentricity flaws my result in extra vibration, noise emission, and torque pulsations, as well as magnetic and dynamic issues [25].

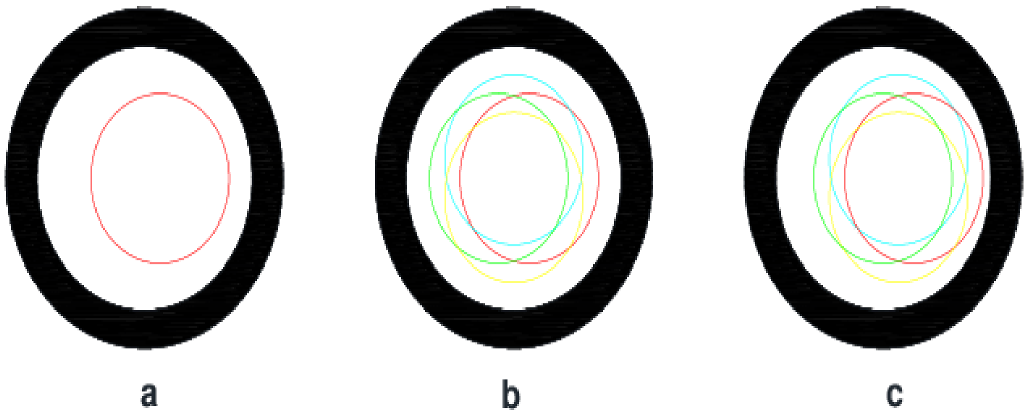


Figure.1.7: Eccentricity faults: a) Static eccentricity b) Dynamic eccentricity c) Mixed eccentricity [27].

1.5.3 Sensor faults

There are electrical and mechanical sensor in any VSD. The mechanical sensors are less reliable than the electrical ones because of the mechanical coupling. The sensor often exhibit the following failure sensor:

a. Intermittent sensor connection
b. Complete sensor outage
c. DC Bias in sensor measurement
d. Sensor gain drop

The most serious error are a and b they mean a temporary or complete lack of information used by the VSD for control purpose. Because these error, there is a risk of closed loop unstability if proper action are not taken. This phenomenon is due to the integral action that is generally included in the control laws to achieve perfect reference tracking. However, if a sensor error is detected and there are still enough functioning sensors, a virtual sensor can replace the erroneous information with the help of an observer, or more sophisticated adaptation schemes can be implemented [28].

1.5.4 Power electronic related faults

These faults are generally related to inverters. Their well-known advantages such as high efficiency, high switching frequency and relative short circuit current carrying capacity, power switches based on insulated gate bipolar transistor (IGBTs) are mostly used. Inverter fed AC motor are vulnerable to variety of problems that might develop at the static converter, the motor, and the control system stages. The drive system's function is halted as a result of all these defects, which also causes unscheduled maintenance brakes, unplanned drive pause might result in significant financial losses, thus the development of trustworthy monitoring, quick fault detection, and fault tolerant drive system management technique is now demanded in the market [29, 30].

There are two types of power devices faults: short circuit faults and open switch faults. Different things, such as the incorrect gate voltage, overvoltage, avalanche stress, or temperature overshoot, might result in a short circuit problem. Short circuit failures are challenging to manage because they quickly generate an excessive over current that might seriously harm other components. Furthermore, there is a very narrow window of between onset of the issue and its collapse. The vast majority of short circuit defect diagnosis technique thus rely on hardware circuits [31].

Due to lifting of a bonding wire brought on by heat cycling, an open switch fault happen. Open switch fault can also brought on by an exceptionally high collector current. There is a current distortion as a result of open switch fault. Through generated noise and vibration, it may lead to secondary issues in other components. An open switch fault in, in contrast to short circuit problem, does not result in significant harm, but it does reduce the overall performance of converter system. Therefore, in order to increase the reliability of the converter system, power device fault diagnosis technique is needed [31].

1.6 Fault tolerance control

Along with the fault detection and diagnosis (FDD) techniques, fault tolerance control (FTC) was created around 20 years ago [32]. Even when a fault occurs, the FTC seeks to maintain system operation using the appropriate FDD technique, FTC system have the capacity to automatically identify component failures. If the controlled system can be safely halted for maintenance or repair, they are capable of preserving overall system stability and desirable performance. In other terms, a Fault Tolerance Control System (FTCS) is a closed loop control system that can tolerate component failures while preserving desired performance and stability features [33].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 [34].

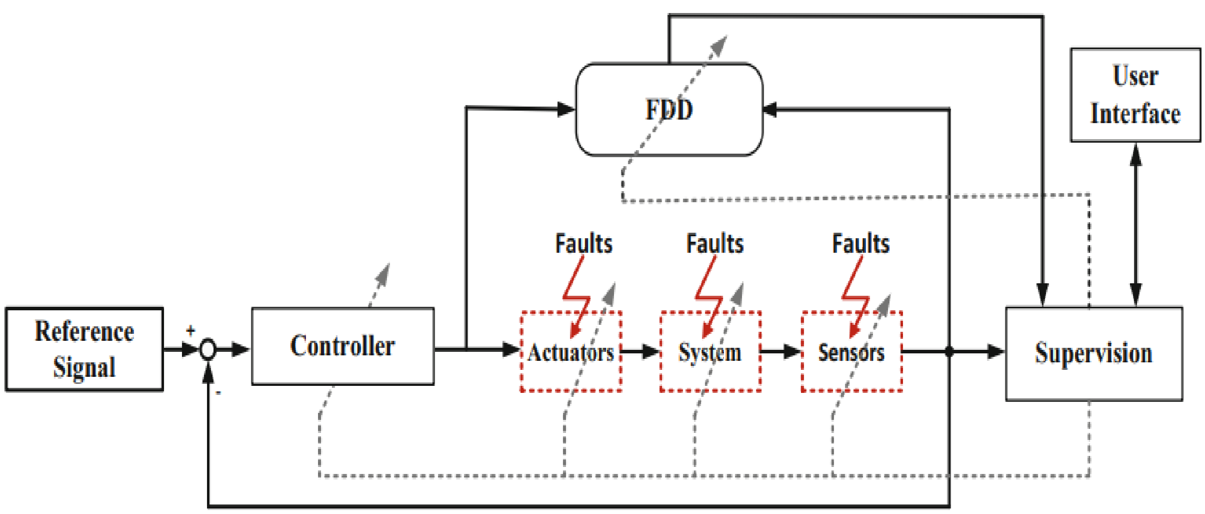


Figure.1.8: The general scheme of FTC system with supervision subsystem [31]

FTC systems based on software (analytic) redundancy are generally divided into two classes: passive and active. Passive FTCs 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 [34]. The general scheme of passive FTC is presented in Fig1.9

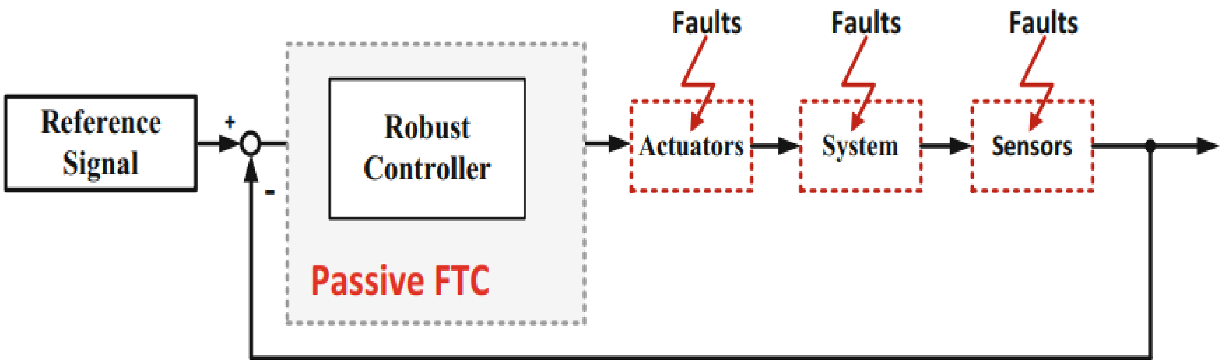


Figure1.9: The scheme of a passive FTC system.

The active FTC systems 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 active FTC system with a FDD unit is presented in Fig .1.10.

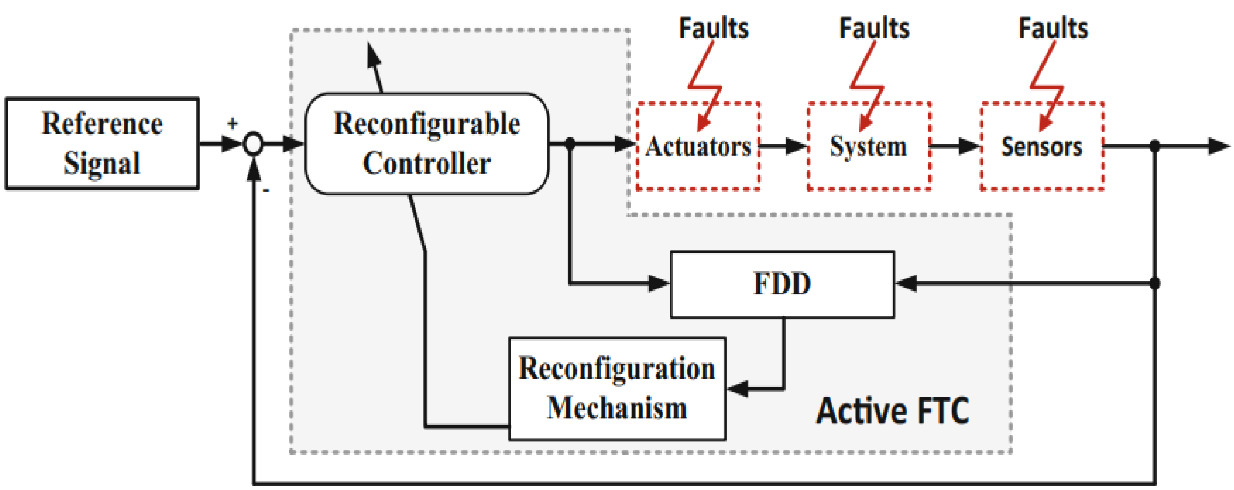


Figure.1.10: The scheme of active FTCS [31]

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. Active FTC systems use dedicated detectors or special state or parameter observers

[33, 34] to identify failure condition. The choice of the proper topology and fault tolerant control algorithm depends on the system requirements and used components.

Conclusion

This chapter consisted of three sections. The first section was an overview on PMSM type and classification. The second section was an introduction to variable frequency drive. The last section dealt with fault tolerance control by first introducing the different fault in PMSM. It then delved into the technique of fault tolerant control based on software redundancy, encompassing both passive and active approaches.

Chapter 2

Modeling & Vector Control of PMSM

2.1 Introduction:

Permanent Magnet Synchronous Motors (PMSM) have received a lot of interest in recent years due to its great efficiency and accuracy in high precision applications, in this chapter, we dig deep into the approach of modeling a PMSM.

At first, we will conduct a sufficient investigation into the steady-state and dynamic properties of PMSM, which is based on the transformation of actual three-phase variables from and to stationary and rotating phasors format , then in the second part the switching states in a three-phase inverter is going to be covered along with Space vector pulse width modulation.

A more complicated control strategy must be used to manage the PM motor in order to achieve better dynamic performance. With the mathematical processing power offered by the microcontrollers, advanced control strategies can be implemented, which use mathematical transformations to control AC machines like DC machines .providing independent control of flux and torque producing currents. Such de-coupled torque and magnetization control is commonly called FOC (field oriented control).

Axes transformation:

Because it is easier to understand the behavior of electrical machines in terms of phasors and their real and imaginary components rather than real three-phase quantities, modern control techniques of adjustable speed drives such as FOC and DTC require the axes transformation from real axes to hypothetical axes.

The theory of axis transformation utilized in electrical engineering is discussed in the next parts

2.2-Stationary reference frame (D-Q plane):

A 3-phase machine can be represented by an equivalent 2-phase machine. Consider a balanced three phase system having voltages Va, Vb, and Vc,

where:
$$\begin{cases} \mathrm{Va} = \mathrm{Vm}\sin(\theta) \\ \mathrm{Vb} = \mathrm{Vm}\sin(\theta - 120) \\ Vc = Vm\sin(\theta + 120) \end{cases}$$

These stationary three-phase voltages (a, b, c) must be converted to stationary two-phase voltages (D and Q)

We can obtain VD and VQ in terms of Va, Vb, and, Vc as following:

$$Vd = Va - Vb\ \cos(60) - Vc\cos(60)$$

$$= Va - ½\,Vb - ½\,Vc$$

$$= Va - \tfrac{1}{2}(Vb + Vc) = \tfrac{3}{2} Va \tag{2.1}$$

$$Vq = Va\cos(90) - Vb\cos(30) - Vc\cos(30)$$

$$= \tfrac{\sqrt{3}}{2}Vc - \tfrac{\sqrt{3}}{2}Vb$$

$$= \sqrt{3}/2\,(Vc - Vb) \tag{2.2}$$

And in matrix form as

$$\begin{bmatrix} V_D \\ V_Q \end{bmatrix} = \begin{bmatrix} \frac{3}{2} & 0 & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

The zero sequence voltage V0 can be introduced in last Equation where V0 is zero

For balanced three phase voltages. And it can be written as:

$$\begin{bmatrix} V_0 \\ V_D \\ V_Q \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ \frac{3}{2} & 0 & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

The abc-voltages can be calculated utilizing the inverse relation as following:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 0 & \frac{2}{3} & 0 \\ \frac{1}{2} & -\frac{1}{3} & -\frac{1}{\sqrt{3}} \\ \frac{1}{2} & -\frac{1}{3} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} V_0 \\ V_D \\ V_Q \end{bmatrix}$$

The previous analysis is also valid for current as following:

$$\begin{bmatrix} i_D \\ i_Q \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & 0 & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

Assume that we have a vector V, where:

$$V = V_D + j\,V_Q \tag{2.3}$$

Substituting (2.4) and (2.5) into (2.10) gives:

$$V = Va - \tfrac{1}{2}Vb - \tfrac{1}{2}Vc + j\left(\tfrac{\sqrt{3}}{2}(-Vb + Vc)\right)$$

$$= Va + \left(-\tfrac{1}{2} - j\tfrac{\sqrt{3}}{2}\right)Vb + \left(-\tfrac{1}{2} + j\tfrac{\sqrt{3}}{2}\right)Vc$$

$$= Va + aVb + a^2Vc$$

Where, $a = e^{-j\frac{2\pi}{3}}$ and $a^2 = e^{j\frac{2\pi}{3}}$

The magnitude of the vector is

$|V| = \sqrt{V_D{}^2 + V_Q{}^2}$

And it's phase:

$\theta = - tang^{-1}(\frac{V_Q}{V_D})$

This composite vector V is called voltage space vector or voltage space phasor. This vector has constant amplitude and rotates in the D-Q plane with fixed speed.

Based on the above analysis, a three-phase system in the a-b-c reference frame may be represented by a single composite vector termed a space vector or space phasor that has constant amplitude and spins at a constant speed in the D-Q frame.

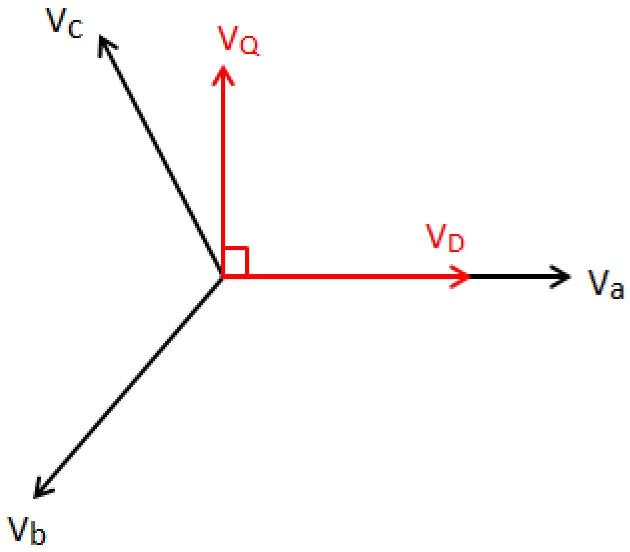


Figure2.1: abc to DQ Axis Transformation

2.3-Rotating Reference Frame (d-q plane):

We can obtain V_d and V_q from V_D and V_Q as following:

$$\begin{cases} V_D = V_d \cos(\Theta r) - V_q \sin(\Theta r) \\ V_Q = V_d \sin(\Theta r) + V_q \cos(\Theta r) \end{cases}$$

And in matrix form:

$$\begin{bmatrix} V_D \\ V_Q \end{bmatrix} = \begin{bmatrix} \cos(\theta r) & -\sin(\theta r) \\ \sin(\theta r) & \cos(\theta r) \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

And inversely:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos(\theta r) & \sin(\theta r) \\ -\sin(\theta r) & \cos(\theta r) \end{bmatrix} \begin{bmatrix} V_D \\ V_Q \end{bmatrix}$$

Defining a space phasor in the rotating reference frame Vdq such that:

$V_{dq} = V_d + j\, V_q$

$= Vd\cos(\theta) + Vq\sin(\theta) + j(-Vd\sin(\theta r) + Vq\cos(\theta r))$

$= Vd(\cos(\theta) - j\sin(\theta r)) + Vq(\sin(\theta) + j\cos(\theta r))$

$= (V_D + jV_Q)e^{-j\theta r}$

Which yields:

$V_{dq} = \mathrm{V}e^{-j\theta r}$ (2.4)

Space vector transformation from the stationary reference frame to the rotating reference frame can be obtained using Equation (2.4)

2.4Machine dynamic model:

The mathematical model of the PMSM is the same as that of the wound rotor SM**,** The derivation of the dynamic model for PMSM in both stationary and rotating reference frames will be derived

2.4.1 Dynamic Model in the Stationary Reference Frame:

The machine's stator voltage space vector (vs) is made up of two parts: one created by the resistive voltage drop via the stator resistance (Rs) and the other by the rate of change of the stator flux linkage (s). In the stationary reference frame, this results in the following equation**:**

$Vs = Rs * Is + \frac{d\Psi s}{dt}$ (2.5)

The stator flux linkage in a PMSM is made up of two components: one formed by stator self-inductance (Ls) and the other by permanent magnets (PM),the rotor angle affects the permanent magnet component of the stator flux linkage. As a result, the stator flux linkage is as follows:

$\Psi s = Ls\, is + \Psi PMe^{j\theta r}$ (2.6)

Note that Ls = Lls + Lm where Lls is the stator leakage inductance and Lm is the magnetizing inductance.

Substitution (2.5) into (2.4) leads to:

$V_s = R_s i_s + L_s \frac{dis}{dt}$ +j ωr ΨPM$e^{j\theta r}$ (2.7)

Where ωr =$\frac{d\omega}{dt}$, and ΨPM and L_s are constants.

Equation (2.6) represents the motor voltage equation in the stationary reference frame. This equation can be decomposed into its D-Q components as following:

$V_{sD} = R_s i_{sD} + i_{sD}\frac{disD}{dt}$ - ωr ΨPM sin(θr)

and

$V_{sQ} = R_s i_{sQ} + L_{sQ}\frac{disQ}{dt}$ + ωr ΨPM cos(θr)

Note that for the surface mounted PMSM type, L_{sD} = L_{sQ} = L_s

2.4.2- Dynamic Model in the Rotating Reference Frame:

Transforming Equation (2.6) into the synchronously rotating reference frame using Equation (2) gives:

$$Vs^r = Rsis^r + \frac{d(Lsis^r)}{dt} + j\omega r(Lsis^r + \Psi pm) \quad (2.8)$$

Where, the superscript "r" means that the quantities are expressed in the rotating reference frame.

Decomposing $Vs^r$and is^r into their corresponding d and q components such that:

Vs^r=vd + j vq and $is^r = id + jiq$ and separating real and imaginary parts of Equation (2.8) yields:

$$Vsd = Rs\, isd + \frac{d(Lsd\, isd+\Psi pm)}{dt} - \omega rLsqisq = Rsisd + \frac{d(\Psi sd)}{dt} - \Psi sq$$

$$Vsq = Rs\, isq + \frac{d(Lsq\, isq)}{dt} + \omega r(Lsd\, isd + \Psi pm)$$

2.5 Three phase voltage source inverter:

Depending on the kind of supply source and the corresponding architecture of the power circuit, dc to ac converters, also known as inverters, are categorized as voltage source inverters (VSIs) or current source inverters (CSIs),Single-phase VSIs are used for low-power applications, whereas three-phase VSIs are used for medium to high-power applications.

The primary goal of these topologies is to offer a three-phase voltage source with control over the amplitude, phase, and frequency of the voltages. Three-phase dc/ac voltage source inverters are widely used in motor drives, active filters, and unified power flow controllers in power systems and uninterrupted power supplies to generate controllable frequency and alternating current voltage magnitudes via various pulse width modulation (PWM) strategies [35].

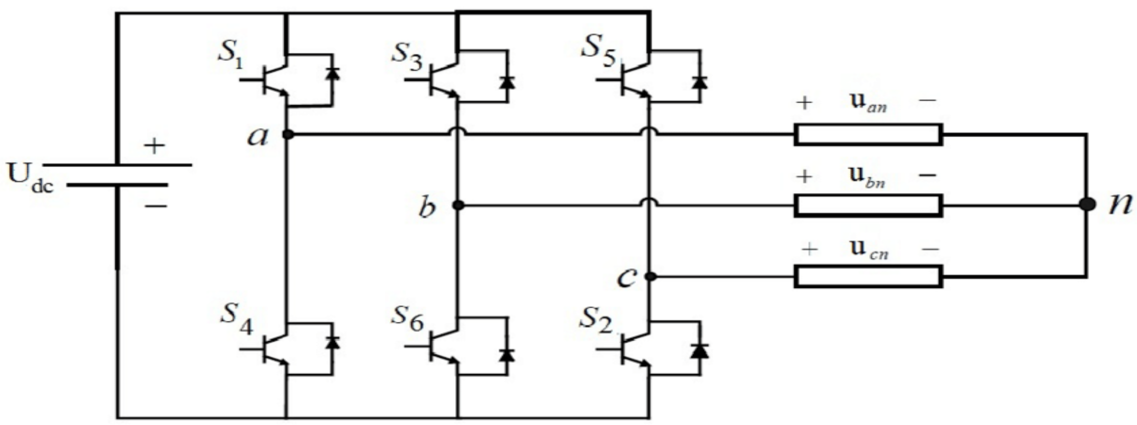


Figure .2.2: Three-phase Full –Bridge Inverter

The inverter has eight switch states, both of the switches in the same leg cannot be turned ON at the same time, as it would short the input voltage violating the KVL.

$$\begin{cases} S11 + S12 = 1 \\ S21 + S22 = 1 \\ S31 + S32 = 1 \end{cases}$$

S11	S12	S31	Vab	Vbc	Vca
0	0	0	0	0	0
0	0	1	0	-Vdc	Vdc
0	1	0	- Vdc	Vdc	0
0	1	1	-Vdc	0	-Vdc
1	0	0	Vdc	0	-Vdc
1	0	1	Vdc	-Vdc	0
1	1	0	0	Vdc	-Vdc
1	1	1	0	0	0

Table 2.1: The switching states in a three-phase inverter

Of the eight switching states, two of them produce zero ac line voltage at the output. In this case, the ac line currents freewheel through either the upper or lower components. The remaining states produce no zero ac output line voltages. In order to generate a given voltage waveform, the inverter switches from one state to another. Thus the resulting ac output line voltages consist of discrete values of voltages, which are -VDC, 0, and VDC.

$$VDC/2\ (S11 - S12) = Van + Vno \tag{2.9}$$

$$VDC/2\ (S21 - S22) = Vbn + Vno \tag{2.10}$$

$$VDC/2\ (S31 - S32) = Vcn + Vno \tag{2.11}$$

Adding the equations we get:

$$\frac{VDC}{2}\ (S11 - S12 + S21 - S22 + S31 - S32) = Van + Vbn + Vcn + 3Vno$$

As we dealing with balanced voltages Van+Vbn+Vcn=0 and using the conditions we get

$$VDC/6\ (2S11 + 2S21 + 2S31 - 3) = Vno$$

Substituting from equations (2.9) to (2.11), gives:

$$\begin{cases} Van = \dfrac{VDC}{3}(2S11 - S21 - S31) \\ Vbn = \dfrac{VDC}{3}(2S22 - S21 - S31) \\ Vcn = \dfrac{VDC}{3}(2S31 - S21 - S11) \end{cases}$$

2.6 Space vector pulse width modulation:

SVPWM is a method used in the final step of field-oriented control (FOC) to identify the pulse-width modulated signals for the inverter switches to provide the required 3-phase voltages to the motor. SVPWM is said to be more efficient than natural or regular sampled PWM.

It has been shown, that SVPWM generates less harmonic distortion in both output voltage and current applied to the phases of an ac motor and provides a more efficient use of the supply voltage in comparison with sinusoidal modulation techniques. SVPWM provides a constant switching frequency and therefore the switching frequency can be adjusted easily. Although SVPWM is more complicated than sinusoidal PWM and hysteresis band current control, it may be implemented easily with modern DSP based control Systems [40].

SVM predicts inverter voltage vectors by projecting the reference vector Vs* across neighboring vectors corresponding to two non-zero switching states.

The switching vectors diagram for a two-level inverter is a hexagon divided into six sectors, each of which is enlarged by 60°.

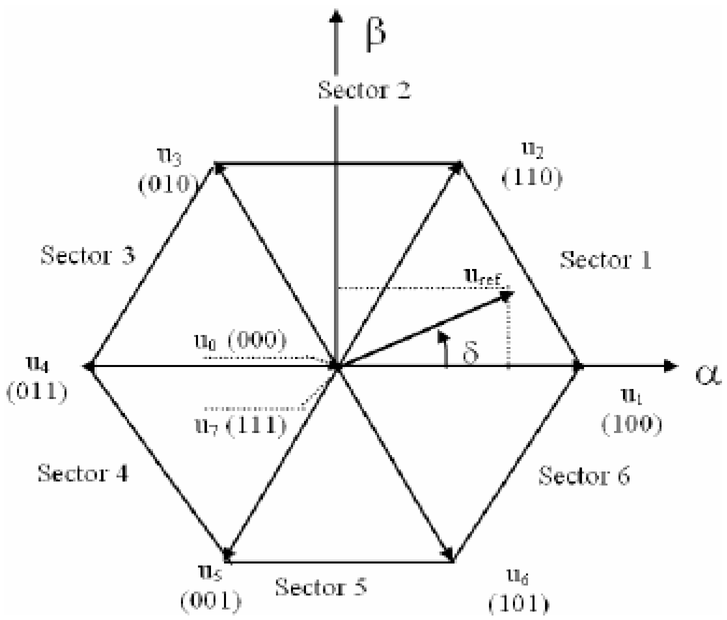


Figure.2.3: Principle of space vector modulation

The space vector modulation method has only eight space vectors at its disposal. However, other space vectors can be synthesized – on average – by alternating several active and zero vectors over a switching period [2].

Switching time duration at sector 1:

$$\int_0^{Tz} \overline{Vref} = \int_0^{T1} V1dt + \int_{T1}^{T1+T2} V2dt + \int_{T1+T2}^{T2} Vo$$

$$Tz\,.Vref = (T1.V1 + T2.V2)$$

$$Tz.|Vref|.\begin{pmatrix} cos(\alpha) \\ sin(\alpha) \end{pmatrix} = T1.\frac{2}{3}Vdc.\begin{pmatrix} 1 \\ 0 \end{pmatrix} + T2.\frac{2}{3}.Vdc.\begin{pmatrix} cos(\frac{\pi}{3}) \\ sin(\frac{\pi}{3}) \end{pmatrix}$$ Where, $0 \leq \alpha \leq 60°$

$$T1 = Tz\,.a\,.\frac{\sin\left(\frac{\pi}{3}-\alpha\right)}{\sin\left(\frac{\pi}{3}\right)}$$ And $$T2 = Tz\,.a\,.\frac{sin(\alpha)}{sin(\frac{\pi}{3})}$$

$T0 = Tz - (T1 + T2)$, [where $Tz = \frac{1}{fz}$ $and\ a = \frac{|Vref|}{\frac{2}{3}Vdc}$]

$T1, T2, T0$ are the corresponding application times of the voltage vectors respectively.

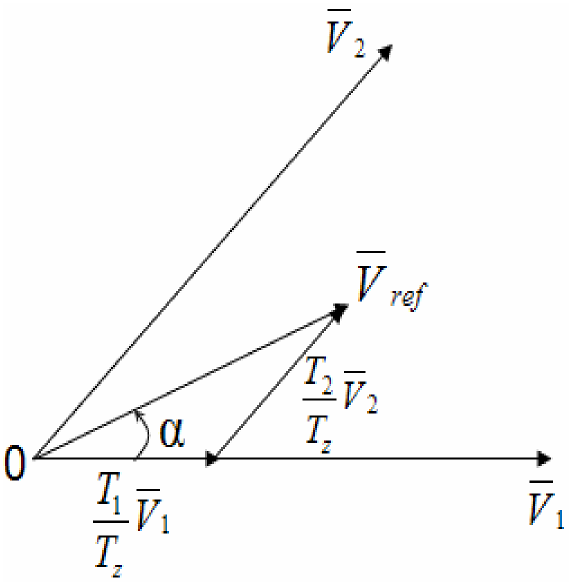
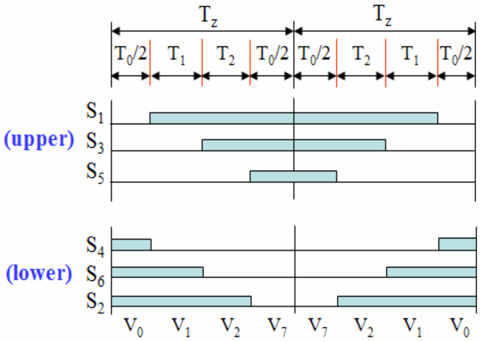
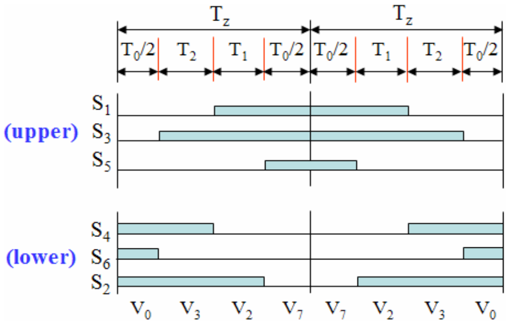


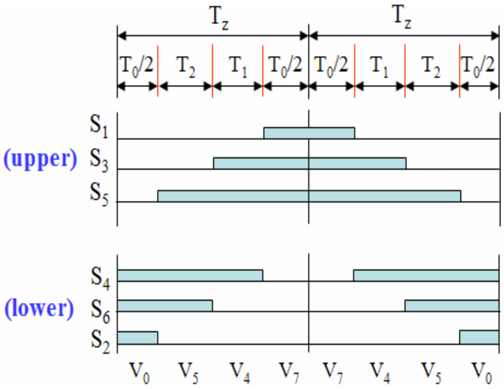
Figure 2.4: Reference vector as a combination of adjacent vectors at sector 1.

The switching time of each transistor (S1 to S6)

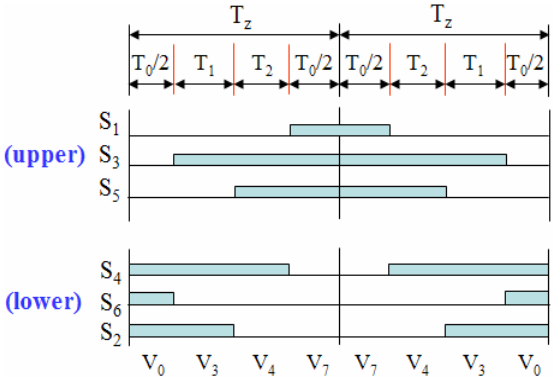




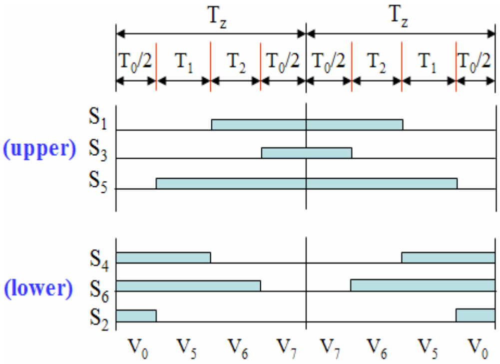
Sector 1sector 2

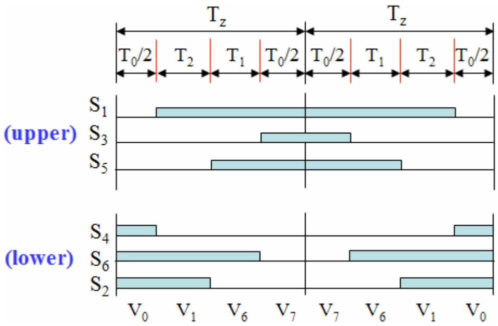


Sector 3



sector 4





Sector 5 **sector 6**

Figure. 2.5: Space Vector PWM switching patterns at each sector.

Based on **Figure 2.5**the switching time at each sectoris summarized in Table 2.2:

Table .2.2: Switching Time Calculation at Each Sector

Sector	Upper switches (s1,s3,s5)	Lower switches (s4,s6,s2)
1	S1=T1+T2+T0/2 S3=T2+T0/2 S5=T0/2	S4=T0/2 S6=T1+T0/2 S2=T1+T2+T0/2
2	S1=T1+T0/2 S3=T1+T2+T0/2 S5=T0/2	S4=T2+T0/2 S6=T0/2 S2=T1+T2+T0/2
3	S1=T0/2 S3=T1+T2+T0/2 S5=T2+T0/2	S4=T1+T2+T0/2 S6=T0/2 S2=T1+T0/2
4	S1=T0/2 S3=T1+T0/2 S5=T1+T2+T0/2	S4=T1+T2+T0/2 S6=T2+T0/2 S2=T0/2
5	S1=T2+T0/2 S3=T0/2 S5=T1+T2+T0/2	S4=T1+T0/2 S6=T1+T2+T0/2 S2=T0/2
6	S1=T1+T2+T0/2 S3=T0/2 S5=T1+T0/2	S4=T0/2 S6=T1+T2+T0/2 S2=T2+T0/2

2.7- Field oriented control of PMSM [4]

2.7.1 -Technical background:

The FOC has direct control over the stator current vector. This control is based on projections, which convert a three-phase, time-variant system into a two-coordinate (d and q co-ordinates) time invariant system. These projections result in a structure resembling that of a DC machine control. As input references, field oriented controlled machines require two constants: the torque component (aligned with the q co-ordinate) and the flux component (aligned with the d co-ordinate). The control mechanism manages immediate electrical quantities because FOC is simply based on projections. This makes the control accurate in all operating conditions (steady state and transient) and independent of the mathematical model's restricted bandwidth.

2.7.2 FOC –SVPWM Method: [39]

Similarly to the induction motor, the FOC method may be used in the PMSM to obtain decoupled control of the torque and flux magnitudes, simulating a DC motor [9]. This is accomplished by the use of the d-q transformation, which separates the components d and q of the stator current that are responsible for flux and torque production, respectively. Because of the permanent magnet's constant flux, there is no need to generate flux via the isd current, and this current can be kept to zero, which reduces the stator current and increases the efficiency of the drive control scheme of the FOC strategy, as shown in Fig (2.6)

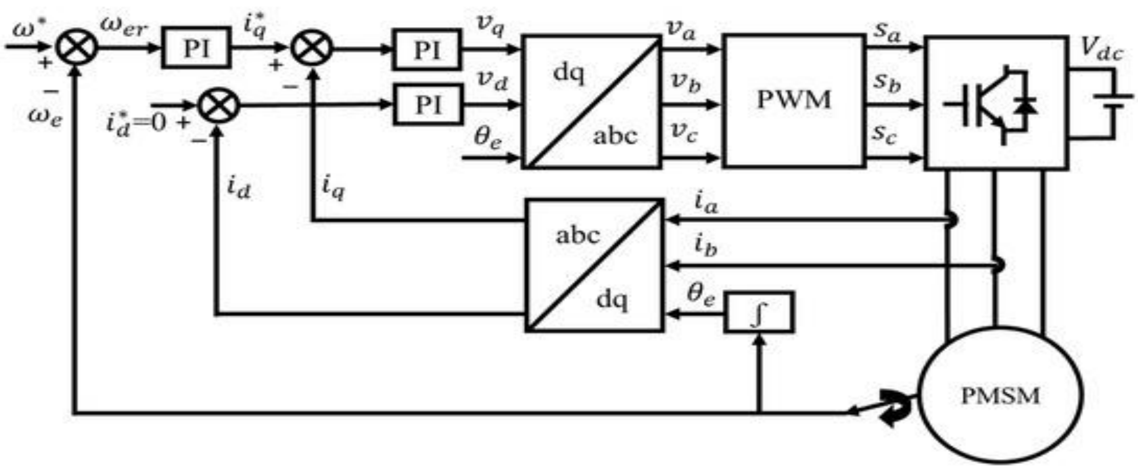


Figure.2.6: global control scheme of field oriented control of PMSM.

The following is a summary of how FOC with SVPWM operates:

1) Measure two of the three motor phase currents and feed them into a Clarke transform to convert them from a three-phase system (i_a, i_b, i_c) to a two-dimensional orthogonal system (i_α, i_β). Note that it's not necessary to measure all three currents, since the sum of the three must equal unity (0). So the third current must be the negative sum of the first two.

2) Apply a Park transform to convert the two-axis stationary system (i_α, i_β) to a two-axis rotating system (i_q, i_d), where the d axis current is aligned to the rotor flux and the d axis current (the torque-producing component) is orthogonal to the rotor flux.

3) The stator current flux and torque are controlled independently, typically by PI controllers. Voltages to be applied to the motor, V_d and V_q, are determined from the PI controllers.

4) Next, an inverse Park transform converts the two-axis rotating system (V_{sqref}, V_{sdref}) back to a two-axis stationary system ($V_{s\alpha ref}$, $V_{s\beta ref}$). These are the components of the stator voltage vector and are the inputs for the SVPWM, which generates the 3-phase output voltage to the motor. (Note that the use of SVPWM eliminates the need for an inverse Clarke transform to obtain the three-phase output voltages.)

2.7.2.1PI speed controller design:

For regulation, proportional-integral (PI) controllers are commonly used. The observed speed value is compared to the speed reference signal. The PI controller then receives the comparison error as input. The pole placement method is used to calculate the controller gains.

The anti-windup controller depicted in figure (2.7) below is the PI controller used in our control scheme's outer speed loop

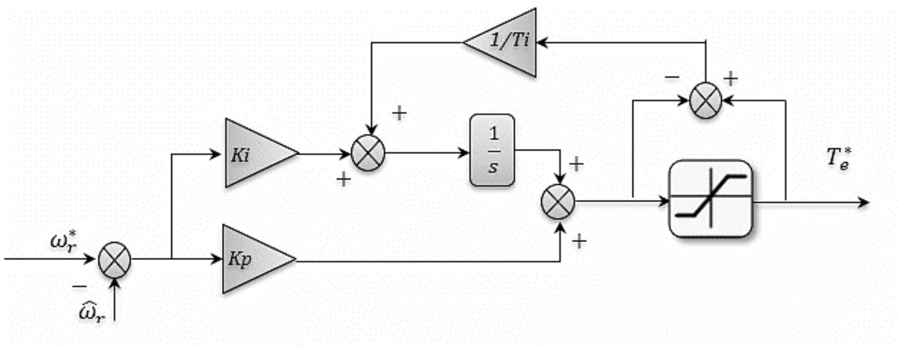


Figure .2.7: Speed anti-windup PI controller

The PI controller has minimum and maximum limits of output, to keep the output within practical values. If a non-zero error signal persists for a long time, the integral component of the controller keeps increasing and may reach a value limited by its bit width. This phenomenon is called integrator windup and must be avoided to have a proper dynamic response. The PI controller IP has an automatic antiwindup function, which limits Integrator as soon as the PI controller reaches saturation.

In field oriented control (FOC) algorithm, there are three PI controllers for Speed, d-axis current Id, and q-axis current Iq. The input of one PI controller depends on the output of the other PI controller and so they are executed sequentially. At any instant, there is only one instance of the PI controller in operation. Hence, instead of using three individual PI controllers, single PI controller is time shared for Speed, Id and Iq for optimum usage of resources. The Speed_Id_Iq_PI module allows sharing of the PI controller through the start and done signals for each of Speed, Id, and Iq. The tuning parameters Kp, Ki, and minimum and maximum limits of each instance of controller can be configured independently through corresponding inputs.

2.8Simulation and Results: Simulation of field- oriented control with space vector pulse width modulation (FOC-SVPWM):

Simulink was used to model the previously described mathematical equations. The simulation included both the controlled motor's starting up and steady-state operation without/with load. The simulation was completed in 0.3 seconds for the three phase non-salient pole rotor 415WSPMSM, whose features are listed in Appendix

Load torque of 5N.m was applied at t=0.02sec, Furthermore, the rotor speed response is compared to a speed reference of 1000 rpm

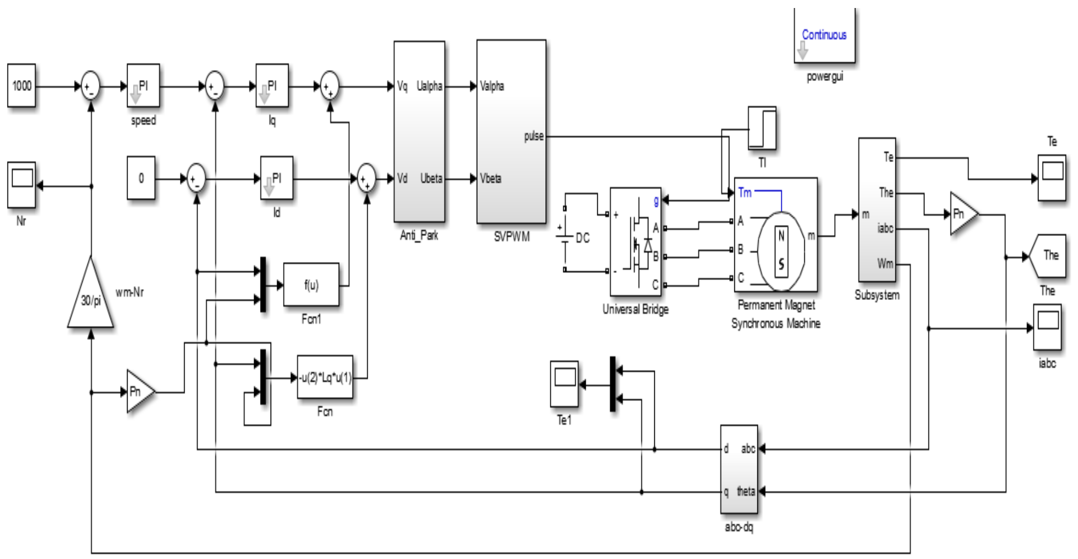


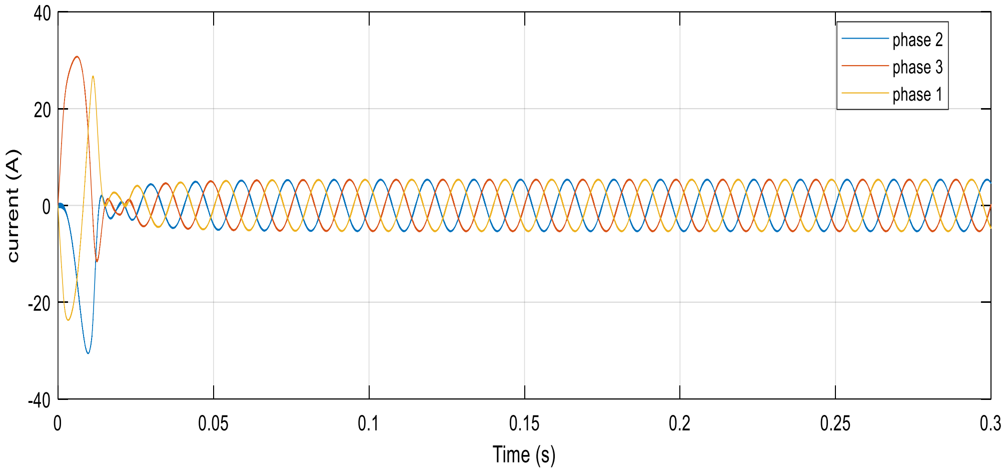
Figure. 2.8 Simulink block of FOC-SVM of SPMSM

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

Simulation results analysis:

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

When a load torque is supplied at t=0.02sec, the motor's speed falls for 0.02se



c before returning to the reference speed. This is known as the torque-speed relationship; they are said to be inversely related (ability to generate torque decreases as speed increases), and the reason for this is because the back EMF resists the supply that is attempting to force current into the stator, which will generate EM-Torque

Stator current analysis:

Figure.2.9: stator currents waveforms

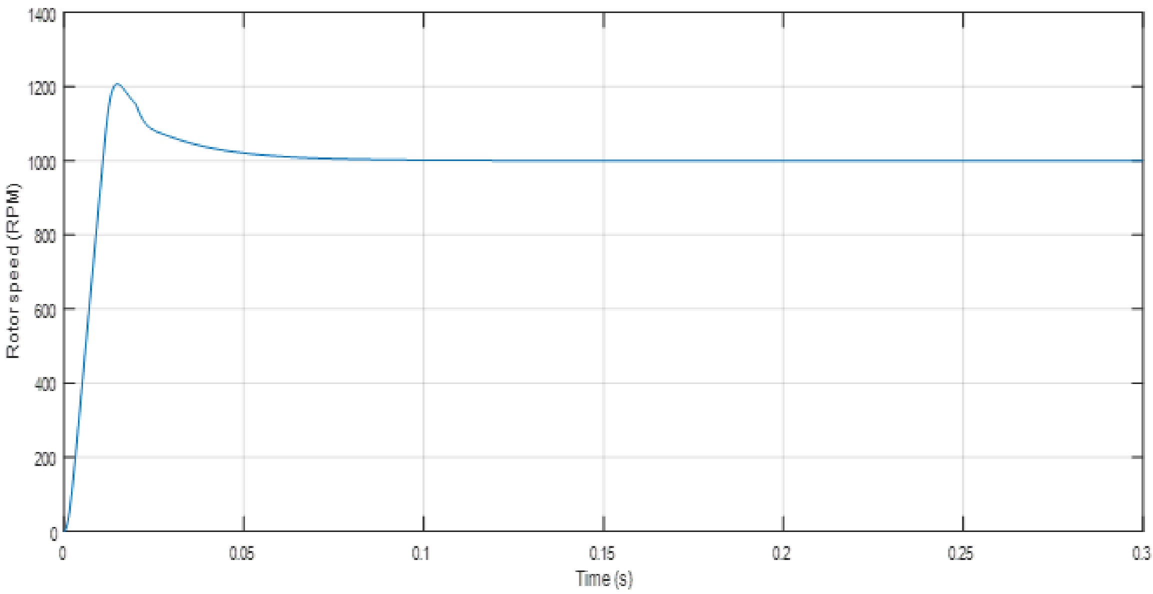


Figure2.10. rotor speed response

Torque response analysis:

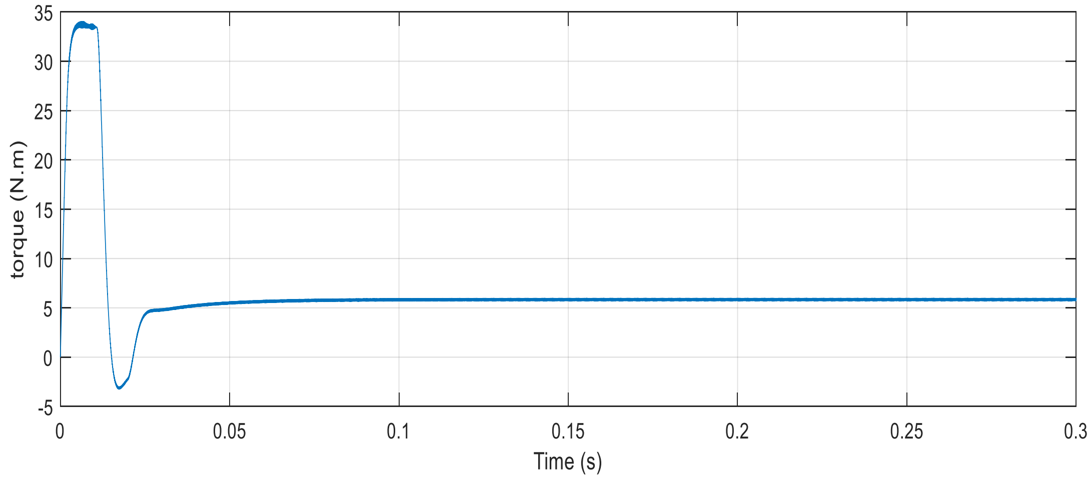


Fig.2.11: torque response

The torque produced by the motor reaches its maximum value (34N.m) and then disappears once the steady state is attained. When load torque is applied, the torque increases to instantly compensate for the load torque, then it match a load torque (5N.m) with a few additional ripples caused by the inverter (but always less than FOC or other control methods in cases where the inverter is not fed by the PWM or SVPWM).

2.9Simulation results conclusion:

A summary of the simulation results indicates that vector control (FOC-SVM) with PI controllers (in the outer and inner loops) for a permanent magnet synchronous motor is a good and efficient control strategy to use. Where the steady states commands were achieved, the PI controllers showed a good dynamic response, because this thesis is about fault tolerant control, we can notice that the simulation results represent the healthy state response to the motor settings and control commands. Those results represent the image of a healthy electric drive system and are sufficient to be used as a reference when we compare them to the results of a faulted electric drive system, which is the task to be done in the following chapter.

Chapter Conclusion:

In This chapter, we discussed the permanent magnet synchronous motor (PMSM), beginning to define its dynamic behavior. These models were stated mathematically in both the stationary and rotating frames using various simplifying assumptions and the general park model. Then, we proposed a three-phase voltage source and vector control technique using space vector pulse width modulation (FOC-SVPWM) to achieve a speed variation of the SPMSM, along with a simulation in Simulink software that yielded satisfactory results**.**

Chapter 3

Fault Detection & Diagnosis Using Fuzzy Logic

3.1. Introduction

Open circuit faults and short circuit faults can be used to broadly categorize power device failures in inverters. Industrial drives now typically include protection against power transistor overcurrent or short circuit, but open circuit failure have not yet gotten as much attention [41]. This type of failure can go unnoticed for long time and may not even result in the system shutting down. This might result in secondary problem with the converter or the other drive parts, which would shout down the entire system and incur large repair expenses.

For these reasons, the development of online methods that can detect open-circuit faults in VSI-fed AC drives, has become an important research field [42].

This chapter covers various open-circuit IGBT fault diagnostic methods for single and multiple open-switch faults in the VSI of FOC-controlled PMSM motor drive systems. A simulation is presented, showing the technique's performance regarding the detection and localization of different faulty power switches.

3.2. Proposed fault diagnosis method

The suggested fault detection method's block diagram is represented in figure.3.1, where the three motor phase currents are the only inputs needed since it is preferable that the fault diagnosis method make use of variables already employed by the main control. Avoiding using more sensors and the inherent rise in system complexity [42].

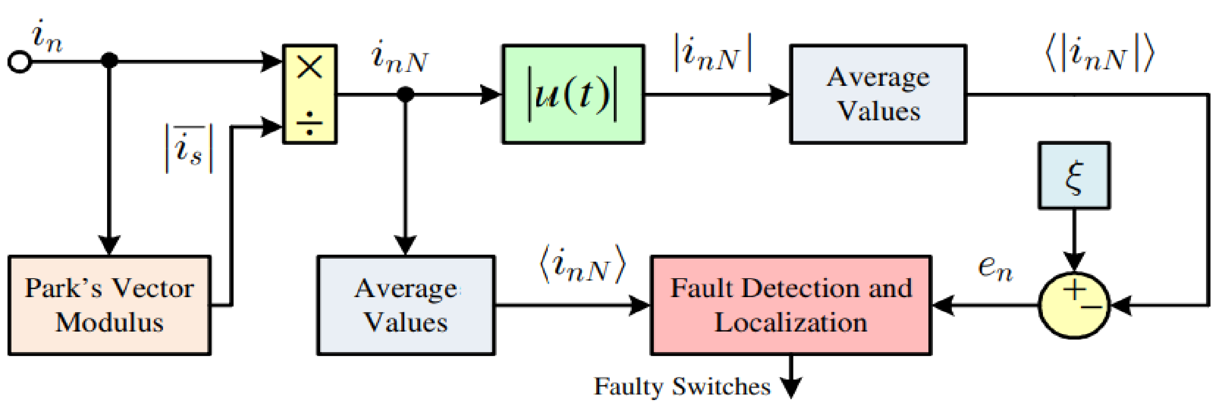


Figure.3.1: Block diagram of the proposed fault diagnostic method.

The measured motor phase current are normalized using the modulus of the park's vector, to overcome the problem associated with the machine mechanical operation conditions dependency and the issue of false diagnostic, defined as:

$$id = \sqrt{\frac{2}{3}} ia - \frac{1}{\sqrt{6}} ib - \frac{1}{\sqrt{6}} ic \quad (3.1)$$

$$iq = \frac{1}{\sqrt{2}} ib - \frac{1}{\sqrt{2}} ic \quad (3.2)$$

Where

i_d and i_q are the park's vector components.

i_a, i_b, and i_c are the motor phase currents

The park's modulus $|\vec{is}|$ is given by

$$|\vec{is}| = \sqrt{id^2 + iq^2} \quad (3.3)$$

The normalization is performed by dividing the motor phase currents by Park's vector modulus. The obtained normalized motor phase currents are given by

$$inN = \frac{in}{|\vec{is}|} \quad (3.4)$$

Where

$n = a, b, c.$

Therefore, assuming that the motor is fed by a healthy inverter generating a perfectly balanced three-phase sinusoidal current system

$$in = \begin{cases} Im\ \sin(wst + \emptyset) \\ Im\ \sin(wst - \frac{2\pi}{3} + \emptyset) \\ Im\ sin(wst + \frac{2\pi}{3} + \emptyset) \end{cases} \quad (3.5)$$

Where I_m is the current maximum amplitude, w_s is the motor currents frequency, and $\emptyset$ is the initial phase angle, it can be proven that Park's vector modulus can be given by

$$|\vec{is}| = Im\sqrt{\frac{2}{3}} \quad (3.6)$$

As a consequence of this normalization process, the normalized motor phase currents will always take values within the range of $\pm\sqrt{\frac{2}{3}}$, independent of the measured motor phase currents amplitude, since

$$inN = \begin{cases} ian = \sqrt{\frac{2}{3}}\ \sin(\mathrm{ws}t + \emptyset) \\ ibn = \sqrt{\frac{2}{3}}\ \sin(wst - \frac{2\pi}{3} + \emptyset) \\ icn = \sqrt{\frac{2}{3}} sin(wst + \frac{2\pi}{3} + \emptyset) \end{cases} \tag{3.7}$$

Under these conditions, the average absolute values of the three normalized motor phase currents$\langle|inN|\rangle$ are given by

$$\frac{2\pi}{ws}\int_0^{\frac{2\pi}{ws}}|inN|dt = \frac{1}{\pi}\sqrt{\frac{8}{3}} \tag{3.8}$$

Finally, the three diagnostic variables are obtained from the errors of the normalized currents' average absolute values, given by

$$en = \xi - \langle|inN|\rangle \tag{3.9}$$

Where ξ is a constant value equivalent to the average absolute value of the normalized motor phase currents under normal operating conditions given by **Eq (3.8)**

$$\xi = \frac{1}{\pi}\sqrt{\frac{8}{3}} \approx 0.5198 \tag{3.10}$$

The three diagnostic variables defined in Eq (3.9) have specific characteristics which allow for the inverter fault diagnosis. When the drive is operating normally, all of the diagnostic variables will be close to zero. However, if an inverter open-circuit fault is introduced, at least one of the diagnostic variables will assume a distinct positive value. Consequently, the errors e_n can be effectively used to detect an anomalous inverter behavior.

However, because these variables only carry information about the affected phases, they are unable to perform a complete inverter diagnostic. As a result, this information, along with the average current values $\langle i_{nN} \rangle$, can be used to identify faulty power switches. To achieve this, fault symptom variables can be formulated according to the following expressions:

$$En = \begin{cases} N & if\ en \le 0 \\ 0 & if\ 0 \le en \le\ kf \\ P & if\ kf \le en \le kd \\ D & if\ en \ge kd \end{cases} \quad (3.11)$$

$$Mn = \begin{cases} L & if\langle inN\rangle\ < 0 \\ H & if\ \langle inN\rangle\ > 0 \end{cases} \quad (3.12)$$

The values taken by E_n and M_n allow to generate a distinct fault signature which corresponds to a specific faulty operating condition. The threshold value k_f is directly related to any fault detection, while k_d plays an important role in the case of a double failure in the same inverter phase. Because the method is normalized, these values do not need to be adjusted for each load and speed condition. They can be empirically established by analysing the behavior of variables under various faulty operating conditions. Taking this into account, the simulation and experimental results enabled the creation of 15 distinct fault signatures, allowing for the effective detection and localization of an equal number of different VSI failure combinations. As a result, considering a typical motor drive system with a VSI supplying an AC motor **(Figure.3.2).** The 15 fault combinations can be detected and identified using **Table 3.1**.

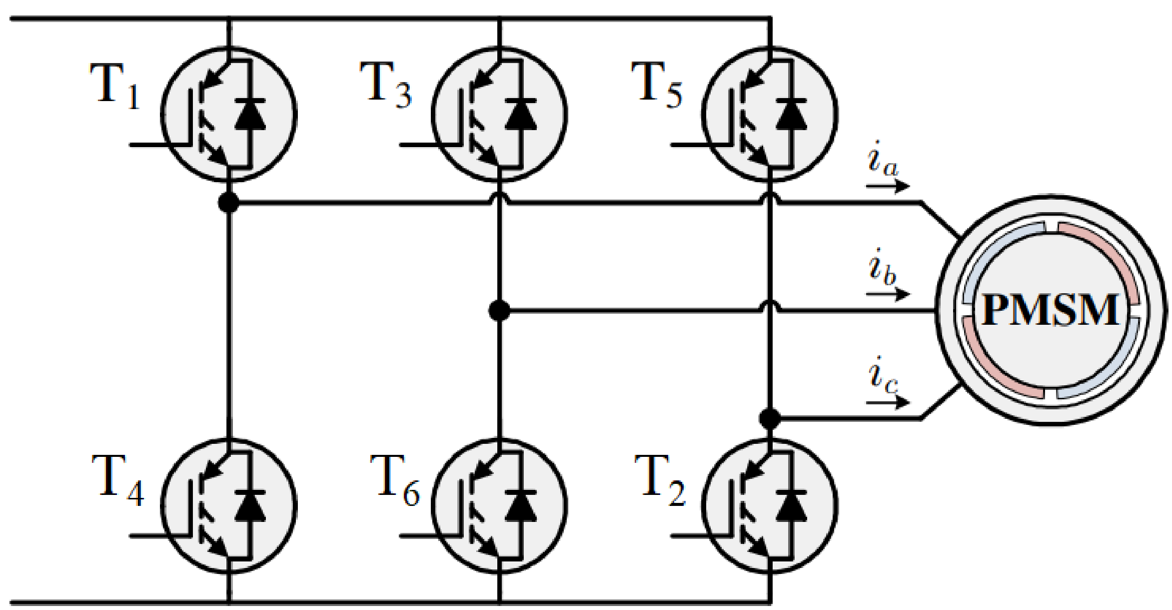


Figure 3.2 diagram of typical VSI feeding PMSM.

3.3. Fuzzy logic fault localization

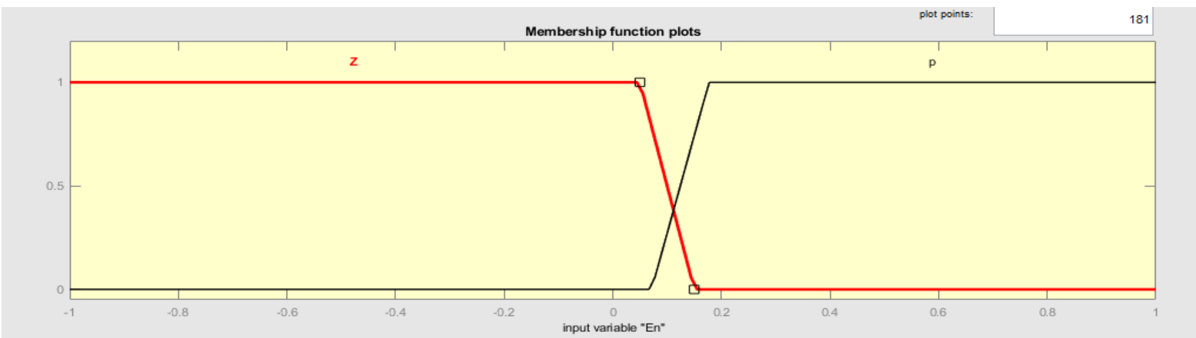
The fuzzy bases of the proposed method are extracted from the analysis of open circuit faulty condition as presented in Equation (3.11) and (3.12) where the fault symptoms variables E_n and M_n should be fuzzed following this steps.

3.3.1. Fuzzy logic problem formulation

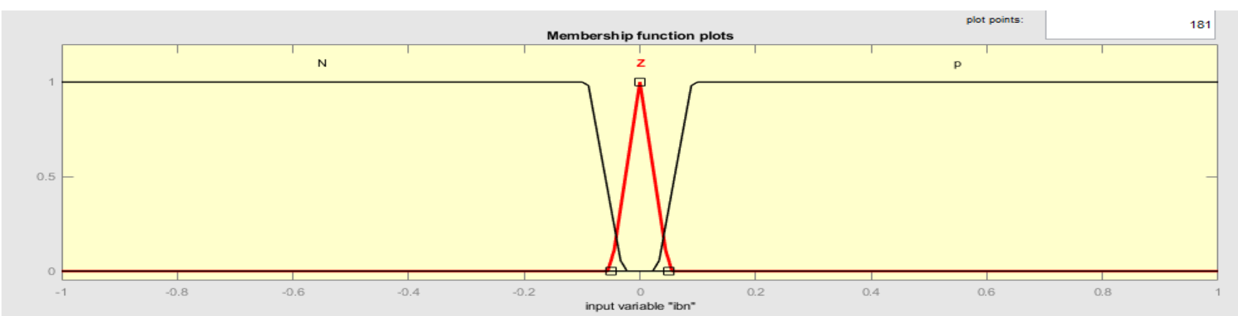
The diagnosis procedure is based on the analytical and heuristic knowledge symptoms of the inverter. Heuristic knowledge in the form of qualitative process models can be expressed as if-then rules. In this paper, the analytical and heuristic symptoms are the fault symptom variables E_n and M_n, which are the input of the fuzzy-based fault diagnosis algorithm. Based on the principle of fuzzy control theory and Equations (3.11) and (3.12), the six fault symptom variables En and Mn should be fuzzified as follows:

$$\begin{cases} En \in \{N, 0, P, D\} \\ Mn \in \{L, H\} \end{cases} \tag{3.13}$$

Figure (3.3) shows the membership functions describing the input variables of the FLA. There are six membership functions according to the above analysis.



(a)



(b)

Figure 3.3. Membership functions of FLA inputs: (a) E_n. (b) M_n

Similarly, the FLA output should be also fuzzified. After fuzzification, the values 0, ±1 indicate the normal operation, intermittent, permanent open-circuit faults of the bottom and/or upper power switches, and finally double open-circuit fault of power switches in the same leg of the inverter. Therefore, the FLA outputs provide not only the open-circuit fault information of a single power switch but also the entire leg fault information.

3.3.2. Fuzzy logic rules

Based on the relationships in Table 3.1, the fuzzy rules can be extracted. In general, the fuzzy control system consists of fuzzification, fuzzy inference, and defuzzification [43] [44].

3.3.2.1. Fuzzification

This first step defines the mapping from normalized input to fuzzy variables by using the membership functions.

3.3.2.2. Fuzzy inference

The second step is fuzzy if-then rules, expressing fuzzy implication relation between the input fuzzy variables and the output fuzzy variables. In the proposed method, a Sugeno type fuzzy inference system is applied.

3.3.2.3. Defuzzification

This third step is the procedure that converts the fuzzy output set back into the crisp values and is called defuzzification. The method used in this paper is the min-max and weighted average “wtsum” method.

The fuzzy rules, summarized in Table3.1, can be extracted and demonstrated as follows:

Leg fault:

- If (E_a = D) and (E_b =Z) and (E_c =Z) then (Leg1 is Leg Fault)
- If (E_a =Z) and (E_b = D) and (E_c =Z) then (Leg2 is Leg Fault)
- If (E_a =Z) and (E_b =Z) and (E_c = D) then (Leg3 is Leg Fault)

Switch fault

- If (E_a = P) and (E_b = Z) and (E_c = Z) and and (Ma = P) then (Switch1)
- If (E_a = P) and (E_b = Z) and (E_c = Z) and and (Ma = N) then (Switch4)

Where $IGBT_{xy}$, {xy: 14, 36, 52}, represents the fault diagnosis flag in the faulty power-semiconductor and Leg_x {x: A, B, C} represents the open-phase fault diagnosis flag. By using these rules, the generated fault signatures allow the detection and localization of the maximum number of faulty modes that can be distinguished.

The block diagram of the proposed fault diagnostics strategy based on fuzzy logic algorithm and current errors is illustrated in **Figure3.4.**

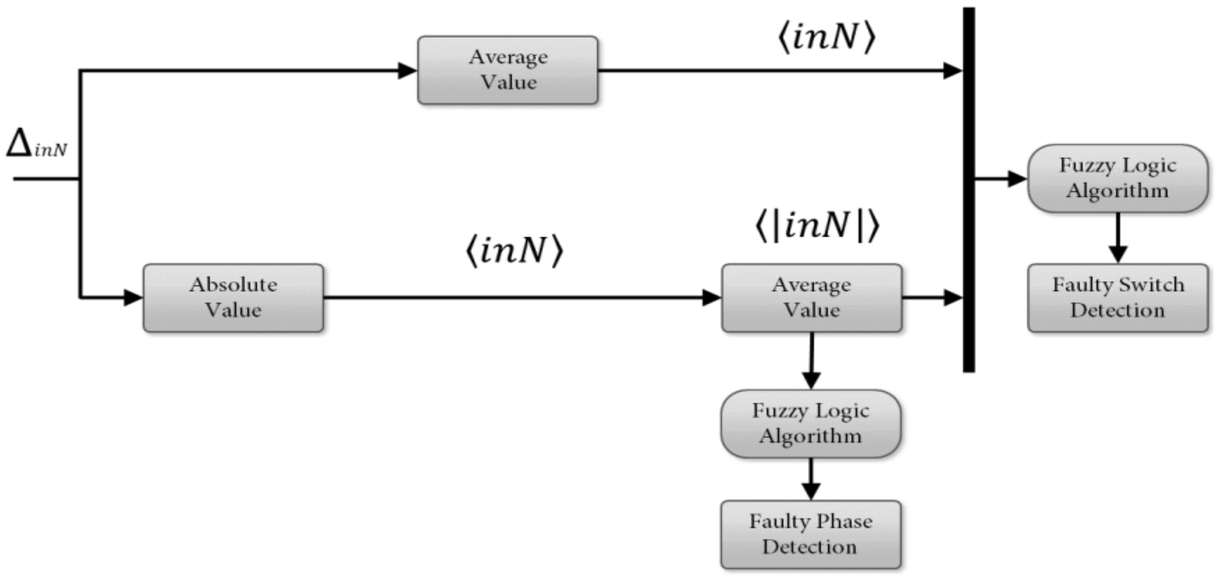


Figure 3.4: Block diagram of the proposed fault detection method using a fuzzy logic algorithm.

Table 3.1 diagnostic signatures for the faulty switches identification

Faulty switch	E_a	E_b	E_c	M_a	M_b	M_c
S1	P	N	N	L	-	-
S4	P	N	N	H	-	-
S3	N	P	N	-	L	-
S6	N	P	N	-	H	-
S5	N	N	P	-	-	L
S2	N	N	P	-	-	H
S1,S4	D	-	-	-	-	-
S3,S6	-	D	-	-	-	-
S5,S2	-	-	D	-	-	-
S1,S3	P	P	N	L	L	H
S4, S6	P	P	N	H	H	L
S3, S5	N	P	P	L	H	L
S6, S2	N	P	P	H	L	H
S1, S5	P	N	P	L	H	L
S4, S2	P	N	P	H	L	H

3.4. Simulation and result

The MATLAB/Simulink environment was used to simulate the driving system of the diagnostic method. A field oriented control strategy was applied to the inverter to control the PMSM mechanical speed.

Some results are provided in order to evaluate the diagnostic method's performance in various failure configurations. In this chapter, three distinct faulty operating conditions are considered: a single IGBT open-circuit fault, a single-phase open-circuit fault (double fault in the same inverter leg), and a double power switch open-circuit fault. All open-circuit faults in power switches are performed by eliminating their respective gate signals while keeping the antiparallel diodes connected (Figure.3.5).

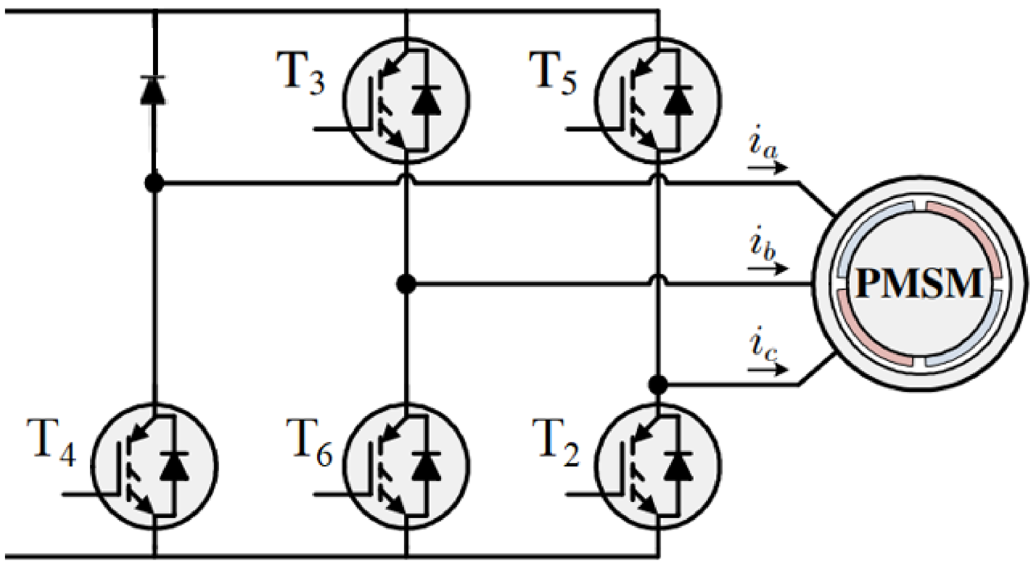


Figure3.5. Three- phase inverter with S1 open switch

For all the considered operating conditions, a load level equivalent to 30% of the PMSM rated torque is assumed, together with a reference speed of 1000 revolutions per minute. For Eq (3.11), the threshold values and are set to be 0.17 and 0.40, respectively.

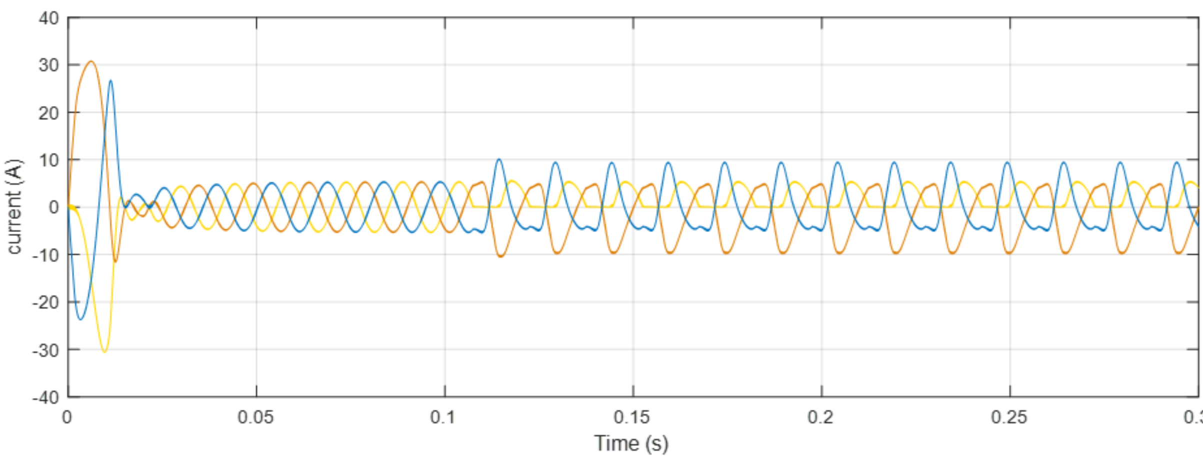
3.4.1. Single IGBT Open-Circuit Fault

3.4.1.1. Fault in transistor S1

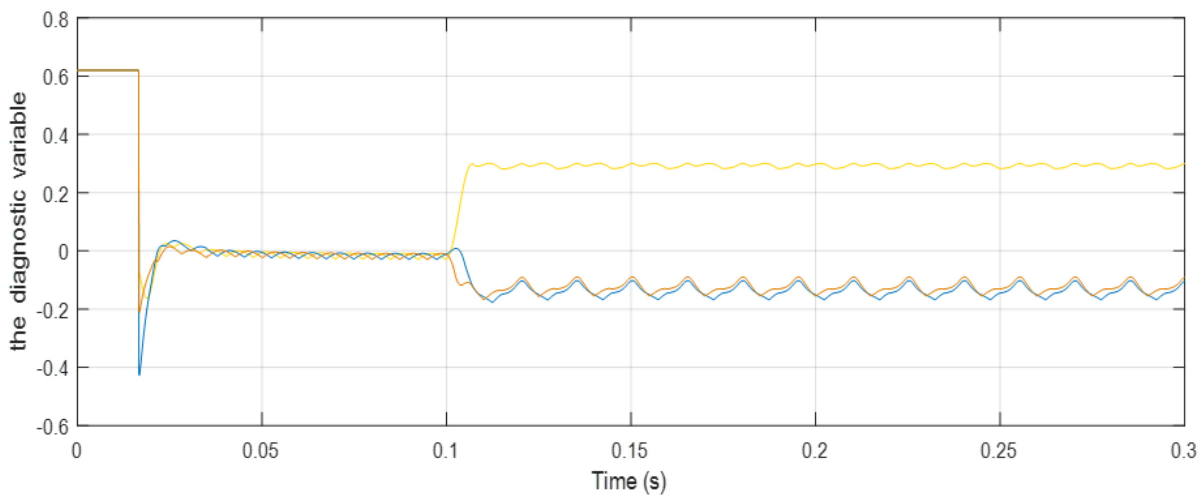
Figure.3.6 illustrates the time-domain waveforms of the motor phase currents, as well as the diagnostic variables and average values of the normalized currents. A load torque of 5N.m is introduced at t=0.02s, and at =0.1s, an IGBT open-circuit fault in transistor S1 is introduced, by removing its corresponding gate signal.

When the fault in IGBT S1 occurs, the diagnostic variable of the corresponding affected phase immediately increases, converging to a value of 0.3. The other two remaining errors will decrease until they reach a value of approximately −0.17 Regarding the normalized currents' average values, since the phase a top switch is in open circuit, the current flow can just be made by the bottom IGBT, resulting in a large negative average value in this phase. ripple appears in rotor speed when the fault occur in S1 as shown in **figure 3.6 (e)**

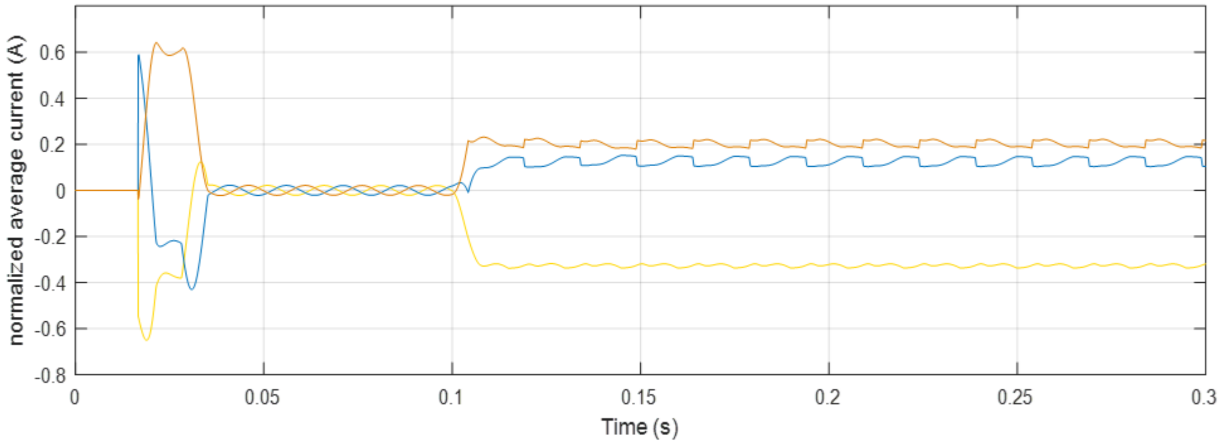
The open-circuit fault is detected 10ms after the fault occurs, based on the defined threshold values and Table.3.1.



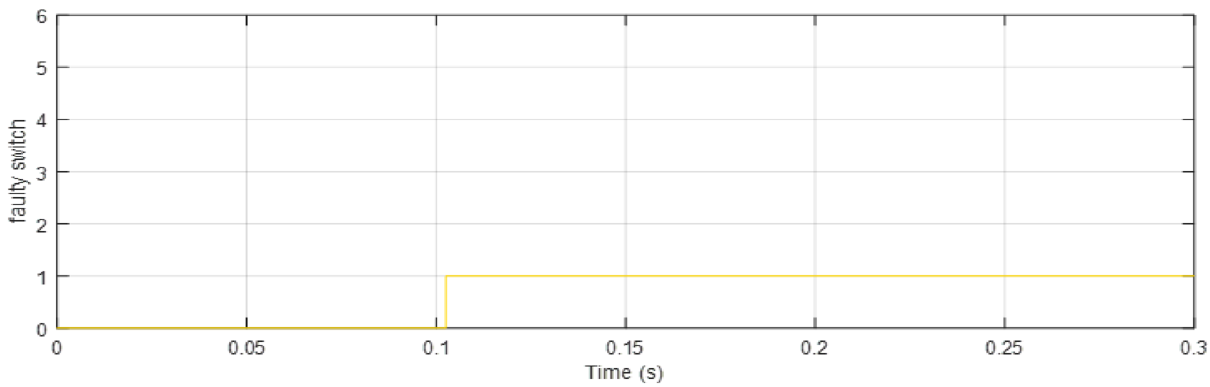
(a)



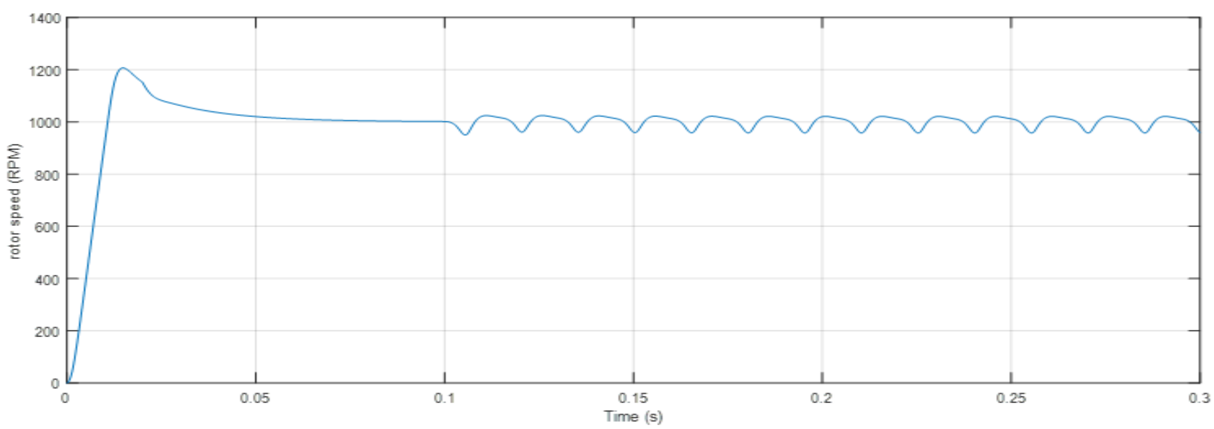
(b)



(c)



(d)

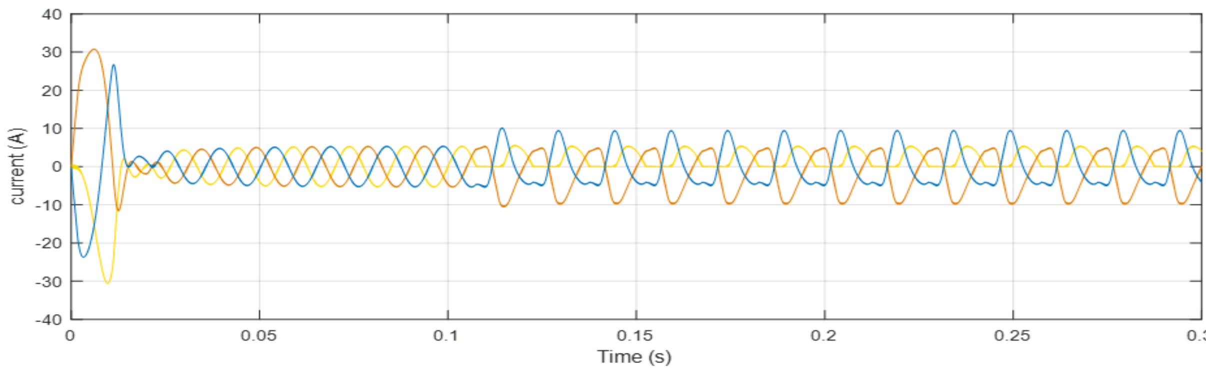


(e)

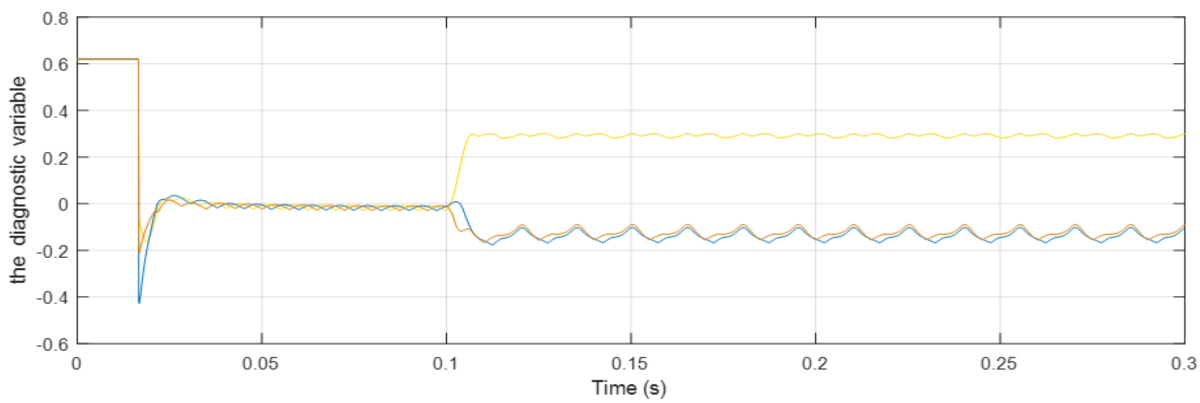
Figure3.6 Simulation results concerning the time-domain waveform of: **(a)** the motor phase currents, **(b)** the diagnostic variables, **(c)** the normalized absolute average value, **(d)** the faulty switch for single open-circuit fault in IGBT S1, and (e) rotor speed under single open switch fault.

3.4.1.2. Fault in transistor S4

The same results have been obtained when the fault is applied on S4 (Figure3.7)



(a)



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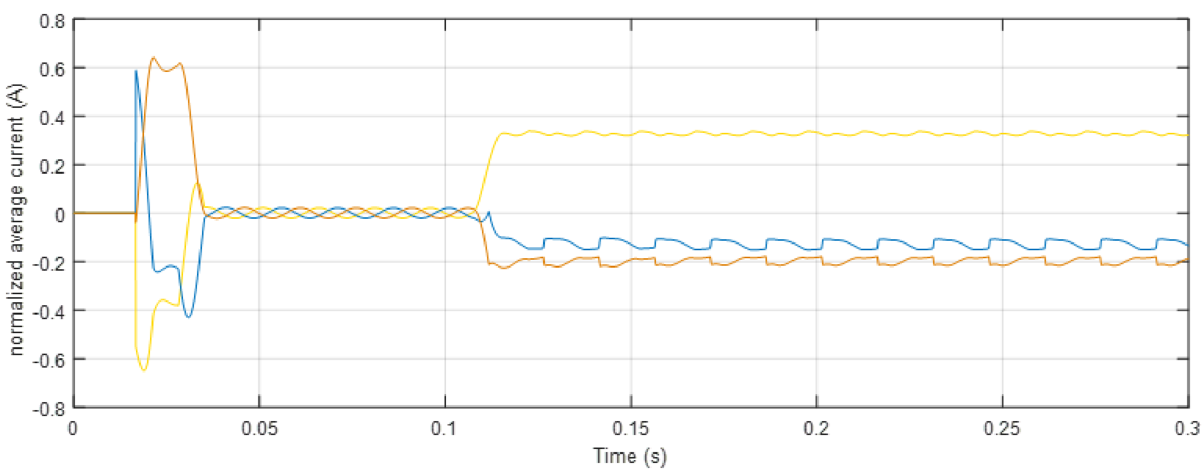

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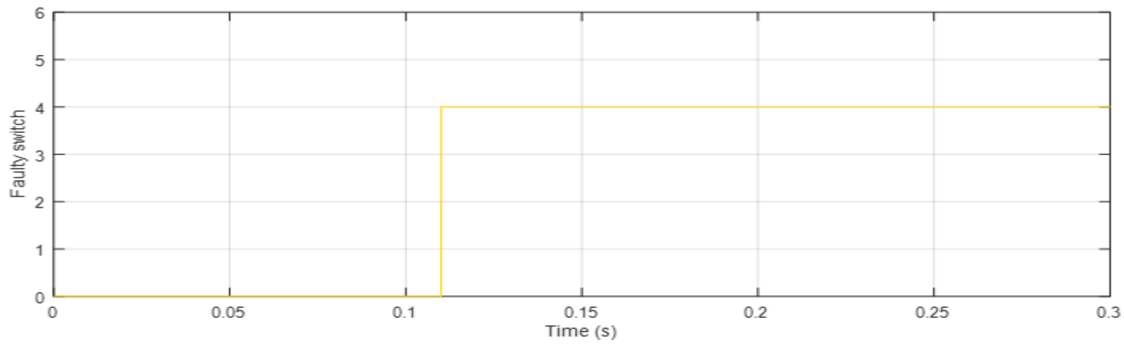


(d)

Figure3.7 Simulation results concerning the time-domain waveform of: **(a)** the motor phase currents, **(b)** the diagnostic variables, **(c)** the normalized absolute average value, and **(d)** the faulty switch for single open-circuit fault in IGBT S4.

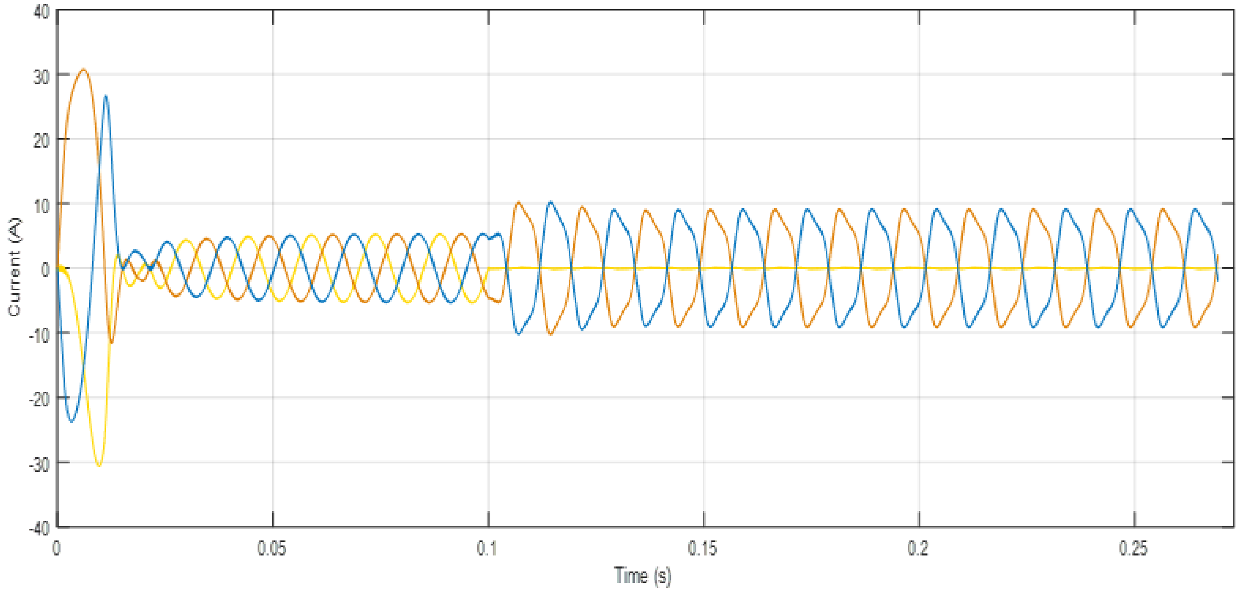
3.4.2. Single phase open-circuit fault

For double failure in power switches S1 and S4 (phase a), figure 3.8 shows the time domains waveforms of the motor phase current, as well as the diagnostic variable, and the normalized currents average value.

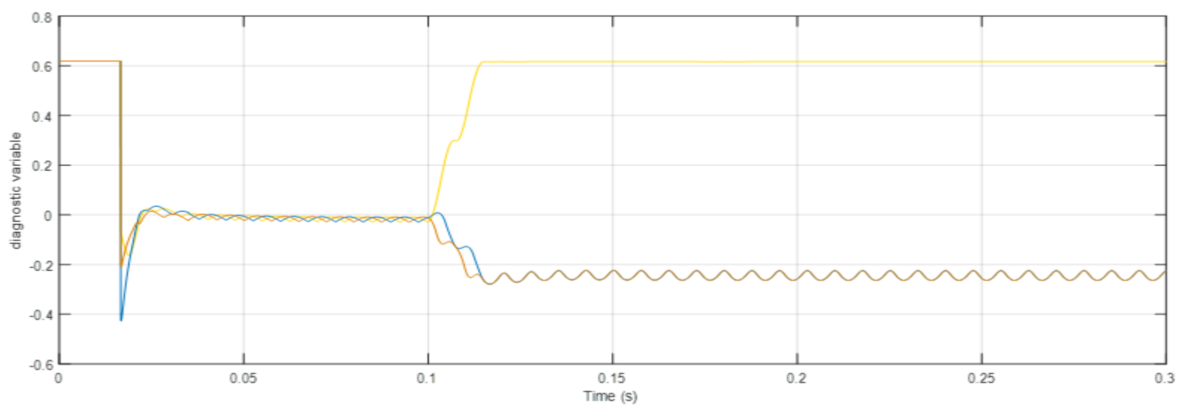
In this case, at the instant t=0.1s, the gate signals are removed from IGBTs S1 and S4, resulting in a single phase open-circuit fault in phase a. As a result, the diagnostic variable will immediately increase to a final value of 0.6. With respect to the two remaining variables, they will decrease, converging both to a value of about -0.25.

When these values are compared to those obtained for a single power switch open-circuit fault, it can be concluded that the final values for a single-phase open-circuit fault are approximately twice those obtained for a single power switch open-circuit fault. Small ripple in rotor speed appears in the speed waveform when the phase (a) is open.

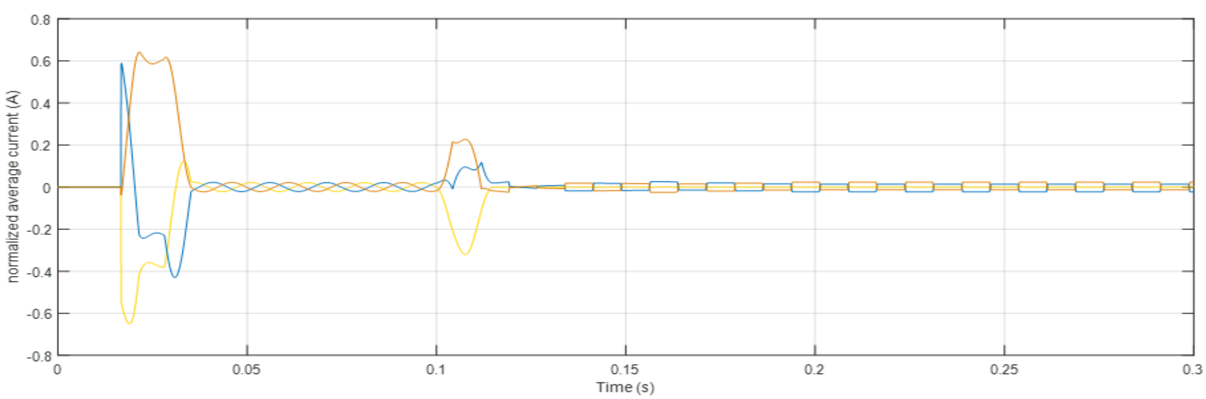
Taking into account the same threshold values and the diagnostic signatures in **Figure.3.8**, the abnormal behavior in phase is also detected 10 ms after the fault occurrence.


Current (A)
Time (s)

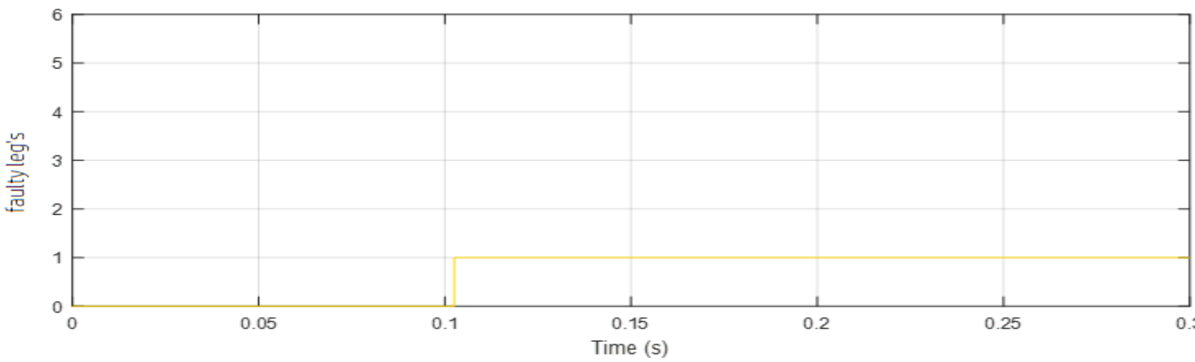
(a)


diagnostic variable
Time (s)

(b)


normalized average current (A)
Time (s)

(c)



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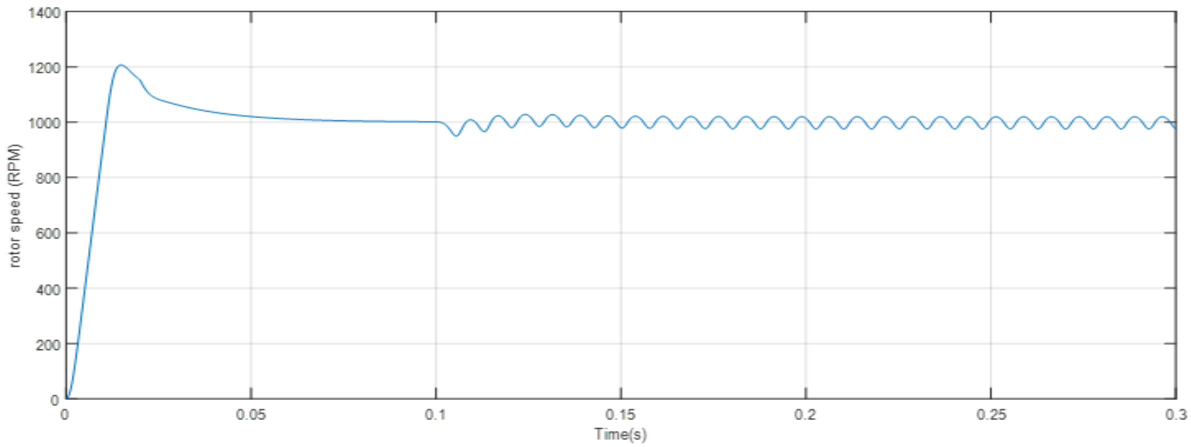


(e)

Figure3.8. Simulation results concerning the time-domain waveforms of: (a) the motor stator current, **(b)** the diagnostic variables, **(c)** the normalized currents average values, **(d)** the faulty leg for a Single-Phase **a** Open-Circuit Fault, **(e)** rotor speed under open phase fault.

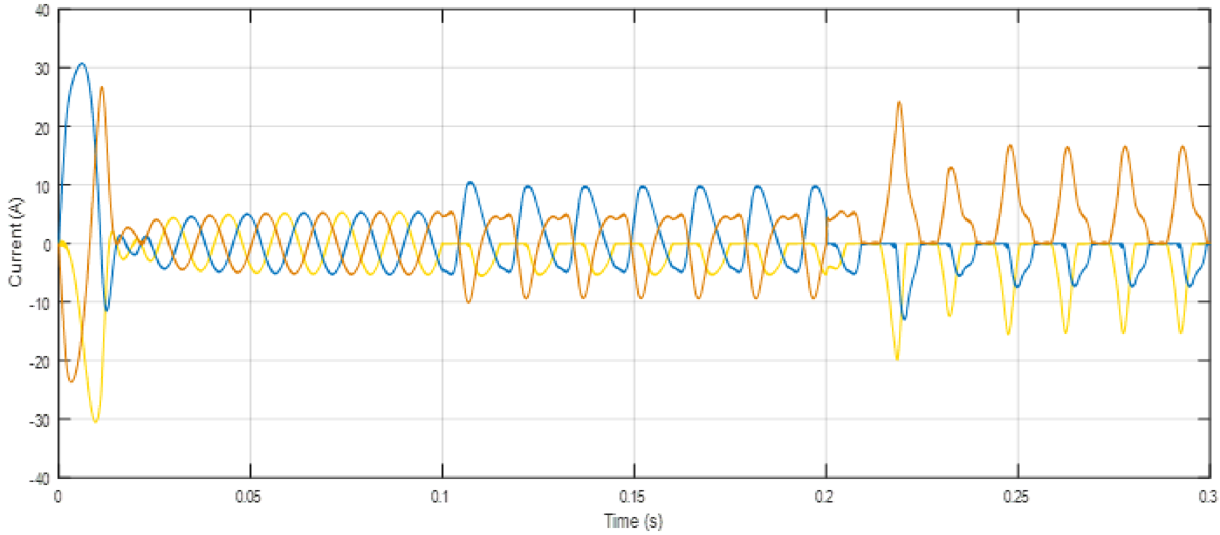
3.4.3. Double power open switch fault

Figure 3.9 shows the time domains waveform of the diagnostic variables and the normalized current average value, for a double fault in switches S1 and S3.

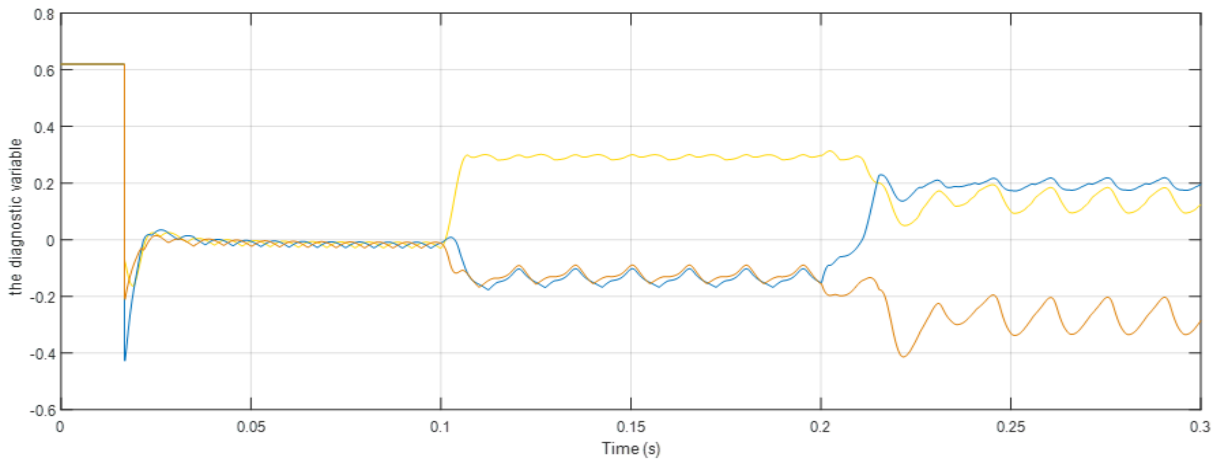
The fault in S1 occur at t=0.1s and the fault of S3 introduced at t=0.2, both diagnostic variable E_a and E_b will increase and reach values higher than K_f as a result of a faulty device on the corresponding phases. On the other side, the diagnostic variable of the healthy phase will converge for a negative value.

Regarding the average values of the normalized currents, it can be seen that the values of the faulty phases will be negative, while the value of phase b will be positive. Therefore, considering the defined threshold values, a unique diagnostic signature is generated, allowing the detection and localization of the faulty IGBTs, according to Table.3.1.

When the fault in S1 is presented at t=0.1s ripple occurs in the rotor speed waveform similar to single open switch fault then after S3 is open at t=0.2s the ripple in rotor speed will increase.



(a)



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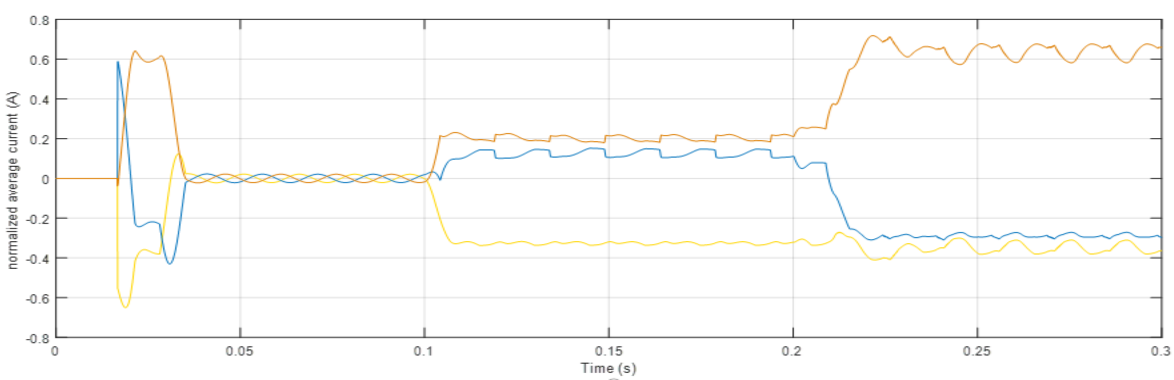

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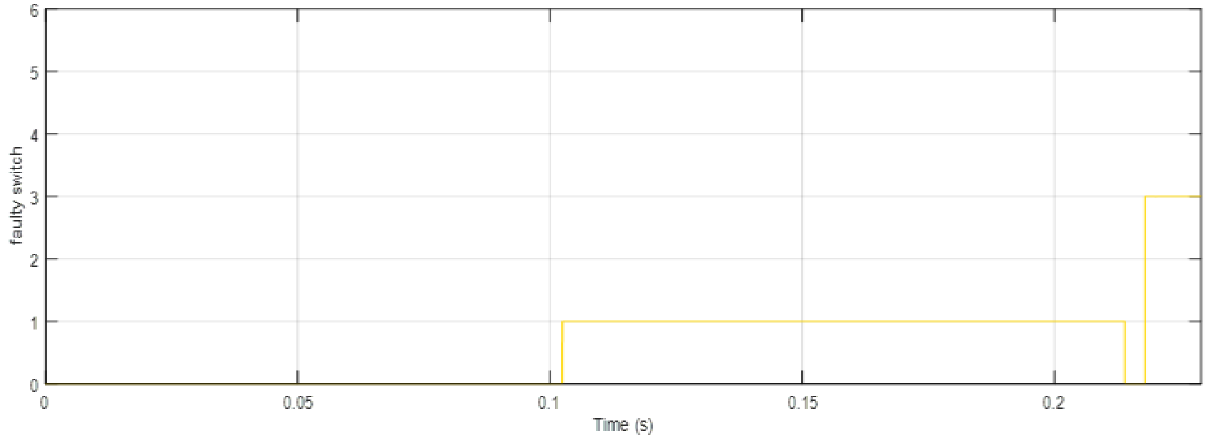

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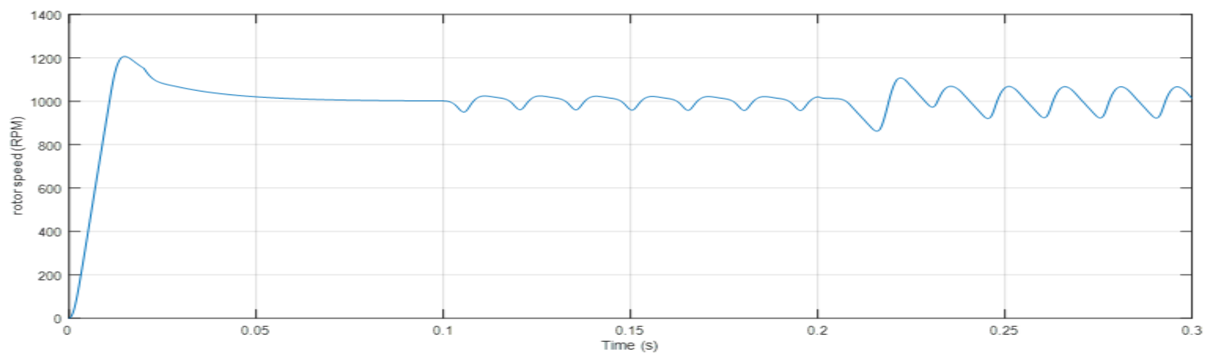


(e)

Figure 3.9. Simulation results concerning the time-domain waveforms of: **(a)** the motor stator currents, **(b)** the diagnostic variables, **(c)** the normalized currents average values, **(d)** the faulty switches for double switch fault in S1 and S3, and **(e)** motor speed under double power switch open-circuit fault in IGBTs S1 and S3.

Further simulation results also proved that the other remaining 11 faulty switch combinations shown in Table.3.1 can be effectively detected and localized.

3.5. Conclusion

This chapter discusses a new method for diagnosing multiple open-circuit faults in voltage source inverter fed induction motor drives. The method only uses the three motor phase currents that are already available for the main control system as inputs.

Taking into account these threshold values, as well as the diagnostic variables and the average values of the normalized currents, 15 distinct fault signatures are generated, each corresponding to a unique inverter failure combination. The algorithm can effectively detect and identify a large number of faulty situations using these signatures.

Finally, since the algorithm is simple and clear, it can be quickly integrated into the main control system. Furthermore, if only the faulty phases were required, some calculations and conditions could be eliminated, making the algorithm even simpler and less computationally demanding.

General Conclusion

General Conclusion

In the past few decades, electrical machines and drives have played a key role in electrification across a wide range of applications. Several initiatives have been introduced to supplant mechanical and hydraulic systems with electrical systems .also In terms of performance, reliability, efficiency, and robustness, electrical systems offer significant advantages .but unfortunately, those machines are exposed to many faults during performance.

In this thesis, the fault detection and localization of three phase permanent magnet synchronous motor using fuzzy logic approach has been studied. The first chapter presented an overview of PMSM and variable frequency drives. In the second chapter, the modeling of our PMSM based on the transformation of actual three-phase variables from and to stationary and rotating phasors format with the principles of field oriented control (FOC) and FOC-SVPWM were explored .The third chapter presented a fault diagnosis ad detection of our motor using fuzzy logic, The effectiveness of the proposed diagnosis method has been done through simulation.

FDD approaches for effective process monitoring have gained considerable attention from both various process-oriented industries as well as academia , and thus many useful process monitoring systems including FDD techniques have been exploited and implemented for several industrial processes . However, there are still lots of difficulties in the implementation of the FDD methods for real industrial processes due to the unique characteristics (e.g :non-linearity, non-stationarity, multimodality, class imbalance, etc.). So, to bridge the moderately large gulf between the theoretical approaches and the implementations, it is necessary to consider novel hybrid approaches as well as to design more elaborate FDD models using various intelligent techniques

In the classic control theory, it is assumed that all the components work properly and precisely. However, experience has taught us that this assumption cannot be guaranteed all the time, and on many occasions, system components might face some faults or failures in their task. These accumulative faults would endanger the controller stability and its performance that cannot be tackled by robust control theories. With the increasing demand for having a reliable and safe controller, the fault-tolerant control (FTC) systems became one of the most attractive topics in the field of advanced control theory, which received a great deal of attention among researchers.

Future work

- Use Fault compensation (redandundy leg topology)
- The use of predictive control method for power converters and drives
- Implementaion of current sensor fault tolerant control
- Use compensation of Four-Switch Three-Phase Inverter (FSTPI) Topology.

Appendix

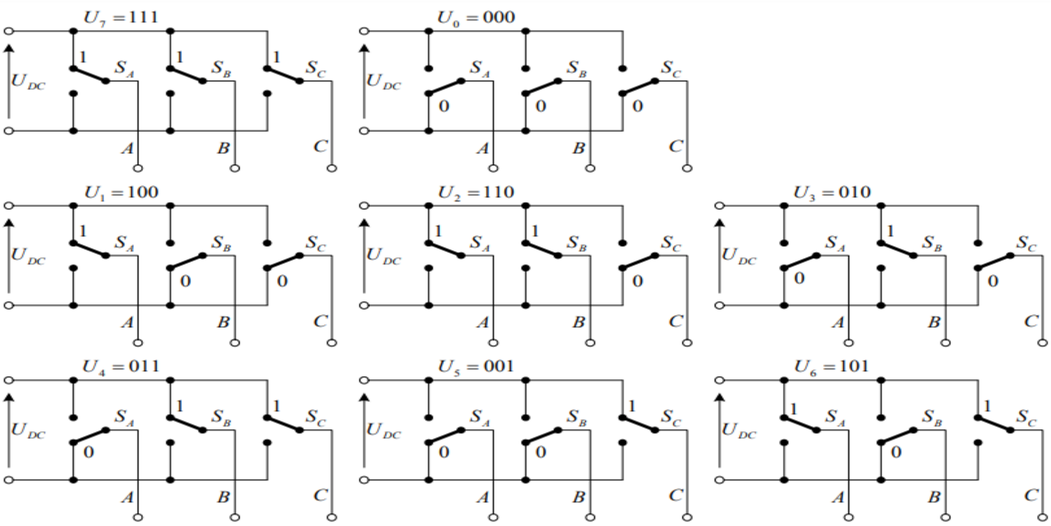
APPENDIX

Appendix A.1

Specifications		Parameters	
Nominal power [W]	415	$R_s = [\Omega]$	0.958
Nominal voltage [V]	360	$L_d = [\mathrm{mH}]$	5.25
Nominal current [A]	4.5	$L_q = [\mathrm{mH}]$	3.12
Number of pole pairs	4	$\psi_r = [\mathrm{Wb}]$	0.3
Nominal speed [rpm]	1500	$J = [\mathrm{Kg.m2}]$	5.5e-3
Nominal torque [N.m]	2.6	$F = [\mathrm{Nm.s.rad^{-1}}]$	0.000005

Table A.1: SPMSM Parameters

Appendix A.2: switches state in voltage source inverter



FigureA.1: Possible switches states in VSI

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