People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University M'Hamed BOUGARA – Boumerdes

Institute of Electrical and Electronic Engineering
Department of Power and Control

Final Year Project Report Presented in Partial Fulfilment of
the Requirements for the Degree of

MASTER

In **Power Engineering**

Option: **Power Engineering**

Title:

Direct Torque Control with Space Vector Modulation of inverter fed Permanent Magnet Synchronous Motor

Presented by:

- **MADDI Liza**
- **REZKI Amazigh**

Supervisor:

Dr. METIDJI

ABSTRACT

In recent years, synchronous motors have become widely used in industrial applications. In all low speed ratings, synchronous motors are physically smaller and less costly to build than squirrel-cage induction motors of equivalent horsepower. Moreover, synchronous motors provide higher torque/inertia ratio and higher efficiency. Particularly, Permanent Magnet Synchronous Motors (PMSM) do not have windings on the rotor. So, there is no need for brushes and slip rings what leads to less copper losses, less maintenance and space saving.

This thesis presents the Direct Torque Control Space Vector Modulation (DTC-SVM) of PMSM. The implementation requires a Digital Signal Processor (DSP) to handle the issue of the control of the PMSM.

The DTC-SVM is one of the preferred methods for motor drives since it operates at a constant switching frequency. This method is based on the estimation of the motor torque and stator flux, comparing the signal with the two adjustable references and compensate the error signals using a PI controller.

The simulation of DTC-SVM model is done using MATLAB/Simulink®. The results are presented to help analyze the system response.

The modeling could also be done using fuzzy logic techniques for better results.

Dedication

To my beloved Mom and Dad

To my lovely Grand Parents

To my sisters Lylia and Kenza

To my husband Nassim

To my best friends Nacera and Loucif

Liza M.

Dedication

I dedicate this work to my lovely parents
My sisters and their families
And all my friends

Amazigh R.

Acknowledgement

We would like to express our gratitude to all people, teachers and friends who helped us to complete this project.

We would like to specially thank our supervisor Dr. Brahim METIDJI for his help, guidance and support through the whole time. It was a great privilege and honor to work under your supervision.

We also acknowledge our teachers and professors specially Dr. Abdelekarim AMMAR for his help through the realization of this thesis.

Finally, we thank all people working at the institute.

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List of acronyms

AC	Alternating Current
DC	Direct Current
DSC	Direct Self Control
DSP	Digital Signal Processor
DTC	Direct Torque Control
FOC	Field Oriented Control
MMF	Magneto-Motive Force
PMSM	Permanent Magnet Synchronous Motor
PWM	Pulse Width Modulation
SVM	Space Vector Modulation
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter

List of variables

i	current quantities
laa,lbb,lcc	self-inductance
lab,lbc,lca	mutual-inductance
R	resistance
$\mathbf{T_e}$	torque
v	voltage quantities
$\mathbf{v_i}$	input DC voltage for the inverter
λ	flux linkage
λm	flux linkage due to permanent magnet

General Introduction

In the last decades, AC machine drives have become more popular especially for induction machines (IM) and permanent magnet synchronous machine (PMSM). PMSMs are getting more popular in industrial applications due to their high efficiency and small size.

With the development of AC drive technology, the variable frequency drives are able to provide smoother speed tuning, greater motor control and fewer energy losses [1]. The VFD can be divided into two major control schemes: Scalar and Vector control.

The scalar control is a simple control technique used to control the machine under steady state. Whereas the vector control is based on the dynamic model of the machine where the voltages currents and flux are expressed in space vector notation [1].

Following the early works of Blaschke and Hasse, and largely due to the pioneering work of Professor Leonhard, vector control of ac machines has become a powerful and frequently adopted technique worldwide. In recent years, numerous important contributions have been made in this field by contributors from many countries, including Canada, Germany, Italy, Japan, the UK, and the USA [2].

Direct Torque Control (DTC) method has been first proposed and applied for induction machines in the mid- 1980's as reported. This concept can also be applied to synchronous drives. Indeed, in the late 1990s, DTC techniques for the interior permanent magnet synchronous machine appeared as reported [3].

However, classical DTC has several disadvantages, from which most important is variable switching frequency. Recently, from the classical DTC methods a new control technique called Direct Torque Control – Space Vector Modulated (DTC-SVM) has been developed.

The DTC SVM is a control method that operates at constant switching frequency to reduce the switching losses and the harmonics. The aim of this technique is to control the flux, torque and speed of the motor for variable speed applications without sensors. The presented scheme has a simple structure implemented using Digital Signal Processor and MATLAB/Simulink.

This thesis is divided into five chapters:

Chapter 1: introduces the PMSM, its operating principle and the mathematical model with the main equations explaining the flux and torque control.

Chapter 2: in this chapter, the different variable frequency control techniques are briefly explained.

Chapter 3: this chapter is divided into three major parts, the first one is about the SVM method in general. The second part deals with the Voltage Source Inverter. The last part is about the basic principles of the DTC SVM control scheme.

Chapter 4: this chapter is devoted for the analysis and synthesis of the DTC SVM simulation using MATLAB/SIMULINK and the interpretation of the results.

Chapter 5: In this chapter, the implementation of the SVM technique has been done using a DSP to control the inverter fed AC motor. The results of the implementation are shown and compared with the results of the simulation

1.1. Introduction

This chapter is going to deal with the explanation of the Permanent Magnet Synchronous Motor, that is the machine that has been chosen to work on in this thesis. This type of machines is getting wilder used in various applications due to their numerous advantages over the other types of machines. In what follows, we will explain the construction and the operating principle, this allows to understand the mathematical model of the machine and hence, simplifying the its different command techniques.

1.2. Construction

The construction of a synchronous motor is very similar to the construction of an alternator. Both are synchronous machines where one is used as a motor and the other as a generator. Just like any other motor, the synchronous motor also has a stator and a rotor.

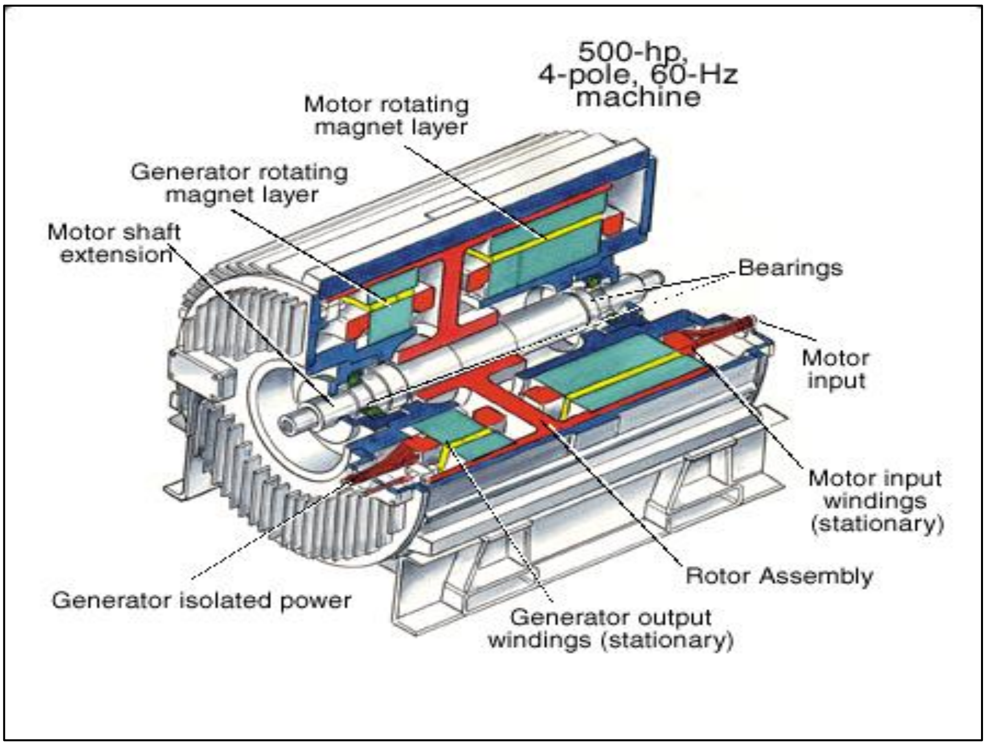


Figure 1.1: Overview of synchronous machine [4].

1.2.1. Stator of Synchronous Motor

The main stationary part of the machine is stator. The stator consists of the following parts.

Stator Frame: The stator frame is the outer part of the machine and is made up of cast iron. It protects the enter inner parts of the machine [5].

Stator Core: The stator core is made up of thin silicon laminations. It is insulated by a surface coating to minimize hysteresis and eddy current losses. Its main purpose is to provide a path of low reluctance for the magnetic lines of force and accommodate the stator windings [5].

Stator Winding: The stator core has cuts on the inner periphery to accommodate the stator windings. The stator windings could be either three-phase windings or single-phase windings. Enameled copper is used as the winding material. In the case of 3 phase windings, the windings are distributed over several slots. This is done to produce a sinusoidal distribution of EMF [5].

1.2.2. Rotor of Synchronous Motor

The rotor is the moving part of the machine. Rotors are available in two types:

- Salient Pole Type
- Cylindrical Rotor Type

The salient pole type rotor consists of poles projecting out from the rotor surface. It is made up of steel laminations to reduce eddy current losses.

A cylindrical rotor is made from solid forgings of high-grade nickel chrome molybdenum steel forgings of high-grade nickel chrome molybdenum steel. The poles are created by the current flowing through the windings [5].

The synchronous motors can be classified into two categories depending on the construction of the rotor:

Wound rotor carrying DC:

In this case the rotor steel structure can be either cylindrical or salient. In either of these cases the rotor winding carries DC, provided to it through slip rings, or through a rectified voltage of an inside out synchronous generator mounted on the same shaft [6].

Permanent magnet rotor:

In this case instead of supplying DC to the rotor we create a magnetic field attached to it by adding magnets on the rotor. There are many ways to do this and all have the
following effects:

The rotor flux can no longer be controlled externally. It is defined uniquely by the magnets and the geometry,

The machine becomes simpler to construct, at least for small sizes [6].

Depending on the way the magnetic bars are mounted on the rotor, we distinguish two types of PMSMs, Surface PMSM where the magnetic bars are mounted on the surface of the rotor whereas, for the Internal PMSM the magnetic bars are mounted inside the rotor as shown in the next figure:

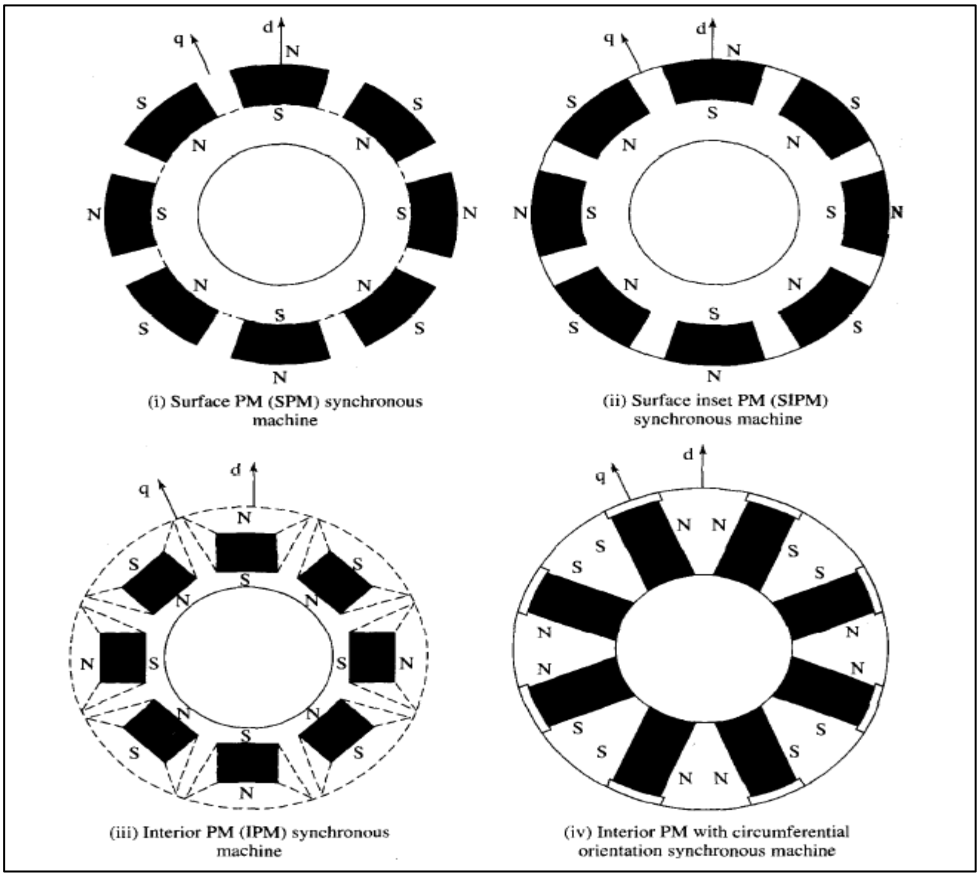


Figure 1.2: Possible placements of magnetic bars in PMSM [6].

1.3. Operating Principle

A synchronous motor, as the name suggests, runs under steady-state conditions at a fixed speed called the synchronous speed. The synchronous speed depends only upon (a) the frequency of the applied voltage and (b) the number of poles in the machine. In other words, the speed of a synchronous motor is independent of the load as long as the load is within the capability of the motor. If the load torque exceeds the maximum torque that can be developed by the motor, the motor simply comes to rest and the average torque developed by it is zero. For this reason, a synchronous motor is not inherently self-starting. Therefore, it must be brought up almost to its synchronous speed by some auxiliary means before it can be synchronized to the supply [7].

The motor comes to operation when the three phase windings of the stator are connected to an external AC source, this will create north and south poles that rotate in a synchronous speed creating a revolving magnetic field. The rotor is mounted on the shaft, it could be of a rare-earth magnet such as Samarium Cobalt or of a ferromagnetic material as Alnico, Aluminum, Nickel and Cobalt alloy. The rotor has to be driven near to the synchronous speed and energized by an external DC source to help the poles of the rotor lock with the poles of the stator. When the poles are locked, the rotor starts rotating at synchronous speed.

Because of its constant speed-torque characteristic, a small synchronous motor is used as a timing device. A large synchronous motor may be used not only to drive a certain load but also to improve the overall power factor (pf) of an industrial plant because it can be operated at a leading power factor. However, when a synchronous motor is operated at no load just to improve the power factor, it is usually referred to as a synchronous condenser [7].

1.4. Mathematical Model Of PMSM

Development of the machine model through the understanding of physics of the machine is the key requirement for any type of electrical machine control. Since in this project a Surface type Permanent Magnet Synchronous Motor (SPMSM) is used for the investigation, the development of this model is under bellow assumptions as:

- Three-phase motor is symmetrical.
- An anisotropy effects, magnetic saturation, iron loses and eddy currents are not taking into considerations.
- The coil resistances and reactance are taking to be constant.
- In many cases, especially when is considered steady state, the currents and voltages are assumed to be sinusoidal.
- Thermal effect for permanent magnets is omitted.

The synchronous motor model will be presented in space vector notation. Space vector form of the machine equations has many advantages such as compact notation, easy algebraic manipulation, and very simple graphical interpretation. Specially, this notation is very useful when analyzing the vector control-based technique of the AC machines [8].

1.4.1. Motor equations in a-b-c frame

The synchronous machine is fed by a three-phase source. The stator windings are considered to be balanced and the phases are separated by 120°.

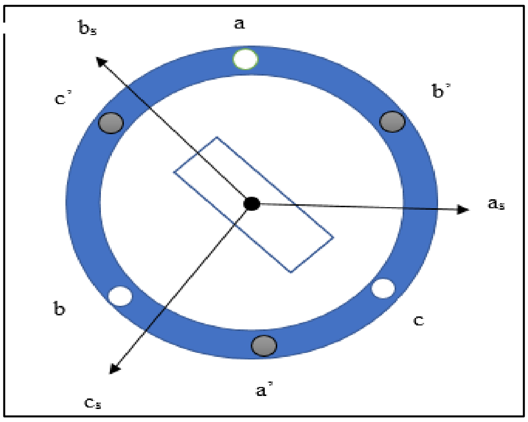


Figure 1.3: A simplified sketch of PM motor showing stator windings and rotor magnet and their magnetic axes.

Applying KVL to the three phases, we get the following equations:

$$v_a = R_a * i_a + \frac{d\lambda_a}{dt} \tag{1.1}$$

$$v_b = R_b * i_b + \frac{d\lambda_b}{dt} \tag{1.2}$$

$$v_c = R_c * i_c + \frac{d\lambda_c}{dt} \tag{1.3}$$

Since the stator windings are wound with the same number of coils, we have

$$Ra = Rb = Rc = Rs \tag{1.4}$$

The magnetic flux linkages are produced by stator and rotor windings and they are functions of inductances and currents:

$$\lambda_a = l_{aa} * i_a + l_{ab} * i_b + l_{ac} * i_c + \lambda_{ma} \tag{1.5}$$

$$\lambda_b = l_{ba} * i_a + l_{bb} * i_b + l_{bc} * i_c + \lambda_{mb} \tag{1.6}$$

$$\lambda_c = l_{ca} * i_a + l_{cb} * i_b + l_{cc} * i_c + \lambda_{mc} \tag{1.7}$$

The flux linkage equations due to permanent magnet:

$$\lambda_{ma} = \lambda_m * \cos(\theta) \tag{1.8}$$

$$\lambda_{mb} = \lambda_m * \cos\left(\theta - \frac{2\pi}{3}\right) \tag{1.9}$$

$$\lambda_{mc} = \lambda_m * \cos\left(\theta + \frac{2\pi}{3}\right) \tag{1.10}$$

1.4.2. Transformations

These transformations are done in purpose of simplifying the analysis of the PMSM and being able to get a time independent equation system, the voltage, current and flux quantities are transformed into d-q reference frame by applying the following steps:

Clarke's transformation:

This transformation tends to change a static three phase reference frame into a two-phase reference frame. Thus, it changes the a-b-c parameters to αβ0 by the following equation:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{1.11}$$

The inverse Clarke transformation is given by:

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} \tag{1.12}$$

Park's transformation:

This transformation has to change the static αβ0 frame into a rotation frame by applying the following equations:

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} * \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} \tag{1.13}$$

The inverse park transform can be obtained by:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} * \begin{bmatrix} X_d \\ X_q \end{bmatrix} \tag{1.14}$$

Final transformation:

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} * \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \qquad (1.15)$$

The inverse transformation is obtained by

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} * \begin{bmatrix} X_d \\ X_q \end{bmatrix} \qquad (1.16)$$

1.4.3. Motor equations in d-q frame

By applying the previous transformations to the motor equations in a-b-c frame we get a set of simplified equations for the voltage, flux and torque. The mathematical model of the PMSM system can be expressed in the rotating reference frame (d-q reference frame) by the coming equations.

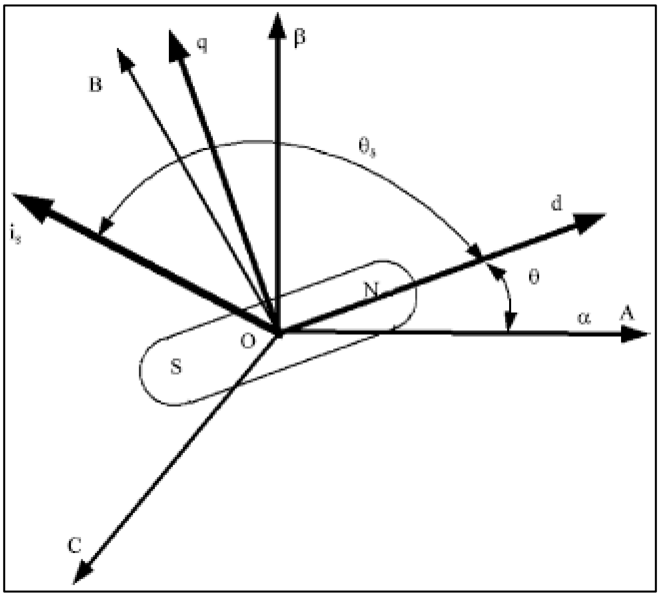


Figure 1.4: Diagram of reference frames and vectors [9].

$$v_q = R_s * I_q + \frac{d\lambda_q}{dt} - \omega * \frac{d\lambda_d}{dt} \qquad (1.17)$$

$$v_d = R_s * I_d + \frac{d\lambda_d}{dt} - \omega * \frac{d\lambda_q}{dt} \qquad (1.18)$$

$$\lambda_q = L_q * I_q \qquad (1.19)$$

$$\lambda_d = L_d * I_d + \lambda_m \qquad (1.20)$$

And hence, the produced electromagnetic torque:

$$T_e = \left(\frac{3}{2}\right) * \left(\frac{P}{2}\right) * \left(\lambda_d * I_q - \lambda_q * I_d\right) \quad (1.21)$$

1.5. Conclusion

This chapter dealt with the PMSM, it described the construction of the motor, summarized its working principle and the mathematical model of the machine.

The motor equations were presented in both a-b-c frame and d-q reference frame to simplify the analysis and help to understand better the control methods that will be presented in the next chapter

2.1. Introduction

In this section, we will deal with some control techniques of Permanent Magnet Synchronous Motor (PMSM). The control methods can be divided into two major categories: Scalar Control and Vector Control. Each one of them is characterized by some special control methods that will allow, using different algorithms, to control and provide a higher performance of the PMSM.

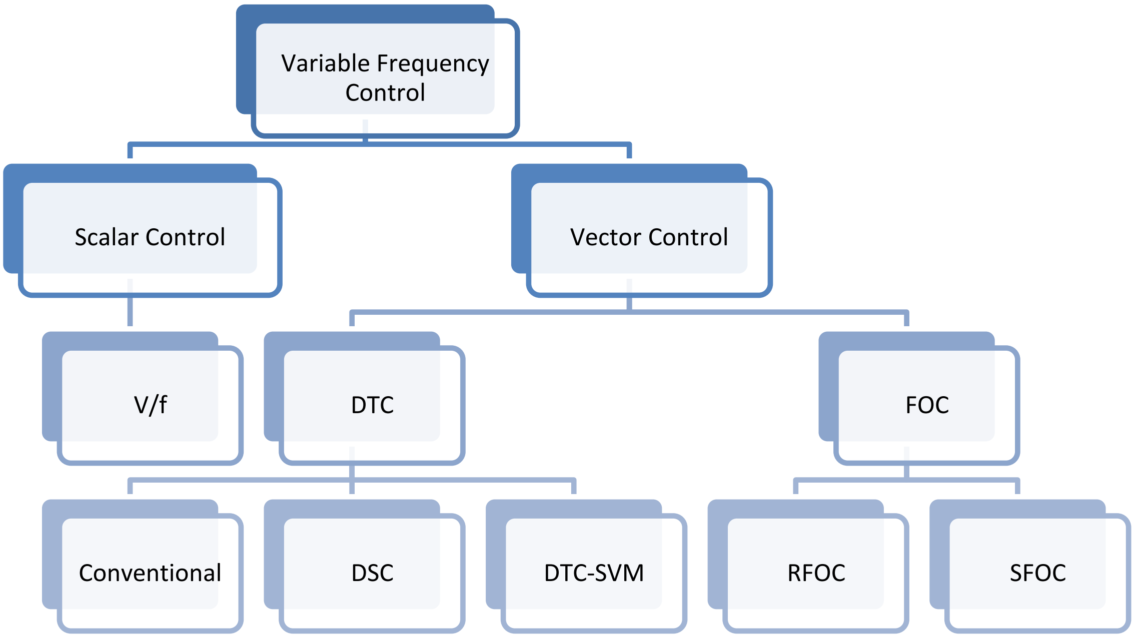


Figure2.1: Some Common Control Techniques Used for PMSM.

2.1. Scalar Control

Scalar control focuses only on the steady state dynamics. One control technique in this category 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.

The main drawbacks of this technique are that the speed control is not accurate and the motor loses stability after exceeding some frequency.

2.2. Vector Control

The problem with Scalar Control is that the motor flux and torque in general are coupled. This inherent coupling affects the response and makes the system prone to instability if it is not considered. In vector control, not only the magnitude of the stator and rotor flux is considered but also their mutual angle [10].

2.2.1. Field Oriented Control (FOC)

The principle of the field-oriented control (FOC) is based on an analogy to the separately excited dc motor. In this motor flux and torque can be controlled independently. The control algorithm can be implemented using simple regulators, e.g. PI-regulators [11].

It is also known as Vector Control. Vector Control decouples three phase stator current into two phase d-q axis current, one producing flux and other producing torque. So, by using Vector Control the PMSM is equivalent to a separately excited DC machine [12].

2.2.2. Direct Torque Control (DTC)

In addition to vector control systems, instantaneous torque control yielding fast torque response can also be obtained by employing direct torque control. Direct torque control was developed more than a decade ago by Japanese and German researchers (Takahashi and Noguchi 1984, 1985; Depenbrock 1985) [2].
DTC has been improved over the years, now we get different methods of DTC that will be briefly discussed in this section.

2.2.2.1. Conventional DTC

In a DTC drive, flux linkage and electromagnetic torque are controlled directly and independently. This is achieved by controlling the stator flux linkage vector by selecting the most appropriate voltage vector at every switching instant. The voltage vectors are selected based on the consideration that the voltage component tangent to the flux linkage vector determines the change in electromagnetic torque and the component radial to the flux linkage changes the flux linkage magnitude.

From stator current and voltage measurements the flux linkage and torque are estimated and compared to the reference value. Based on the error in the electromagnetic torque and the flux linkage, the most appropriate voltage vectors are either selected from a look-up table or realized by space vector modulation (SVM).

Although the instantaneous electromagnetic torque is determined by the angle between the rotor flux linkage and the stator flux linkage vectors, the position of the rotor flux linkage vector (determined by the permanent magnets in the rotor) is required e.g. at the start-up of the drive. This is one of the main differences compared to DTC of induction machines where the initial rotor position is not necessary for the control [13].

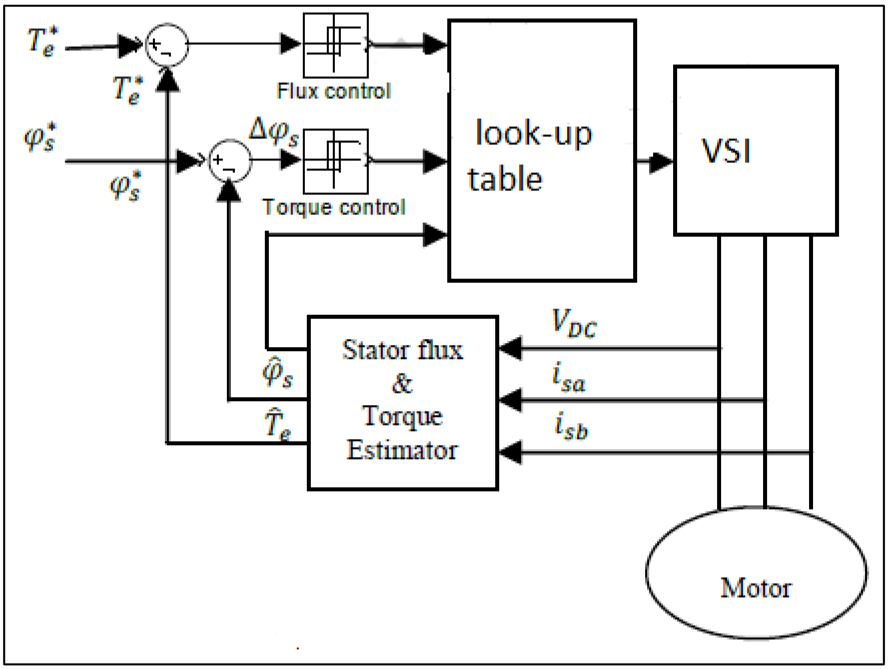


Figure2.2: Block diagram representing the conventional DTC.

Direct Self Control DSC can be considered as special case of DTC with some special characteristics as lower inverter switching frequency than DTC.

2.2.2.2. DTC- Space Vector Modulation (DTC-SVM)

In the DTC-SVM scheme the hysteresis comparators are replaced by an estimator which calculates an appropriate voltage vector to compensate for torque and flux errors. This method has proved to generate very low torque and flux ripple while showing almost as good dynamic performance as the DTC system. The DTC-SVM system, though being a performer, introduces more complexity and lose an essential feature of the DTC, simplicity [10].

2.3. Conclusion

So far, different control techniques have been discussed. The evolution of the control techniques came depending on the problems developed by the previous method. The DTC SVM is characterized by a constant switching frequency what overcomes the problem of ripples and losses of the conventional DTC. This technique will be much more explained in the next chapter

3.1. Introduction

The chapter is devoted for the DTC SVM control technique. First, we will introduce the Voltage Source Inverter (VSI) controlled by the SVM. Next, we will investigate the principle of operation of the DTC SVM to facilitate the modeling of the control strategy.

3.2. Space Vector Modulation control-based Voltage Source Inverter

In this section, we will introduce the power electronic part that is feeding the PMSM. It consists of a Voltage Source Inverter (VSI) controlled using Space Vector Modulation technique (SVM). This strategy is one of the most preferred strategies in Pulse Width Modulation (PWM).

This kind of scheme in voltage source inverter (VSI) drives offers improved bus voltage utilization and less commutation losses. Three-phase inverter voltage control by space-vector modulation includes switching between the two active and zero voltage vectors so that the time interval times the voltages in the chosen sectors equals the command voltage times the time period within each switching cycle. During the switching cycle the reference voltage is assumed to be constant as the time period would be very low. By simple digital calculation of the switching time one can easily implement the SVPWM scheme [14].

3.2.1. Voltage Source Inverter

The inverters are used to convert DC voltage input into an AC output. They are built using semiconductor devices, and generally designed to be single phase or three-phase. However, with the development of multi-phase motors, the inverters also are constructed in such a way to have multiple outputs. The subject of this part will be the three-phase VSI.

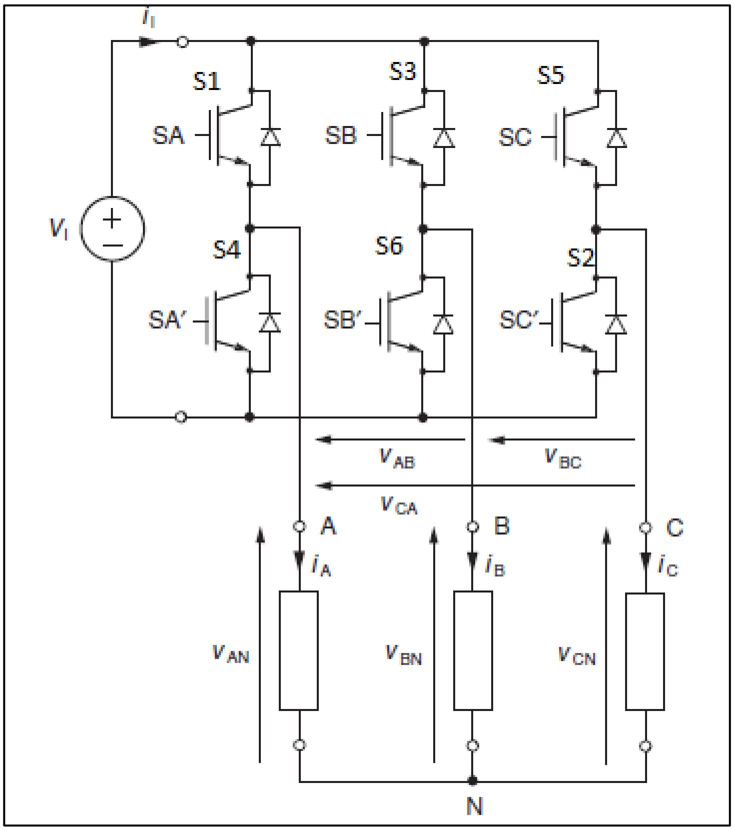


Figure3.1: Three Phase VSI [15].

The circuit model above consists of power six switches controlled by six switching variables SA, SA’, SB, SB’, SC and SC’. When one of the upper switches (S1, S3 and S5) is turned on, the control signal (SA, SB and SC) is said to be 1. Simultaneously, the corresponding down switch is (S6, S4 and S2) is turned off and the control signal (SA’, SB’ and SC’) is said to be 0.

Hence, we have 8 switching states of the inverter shown in the following figure:

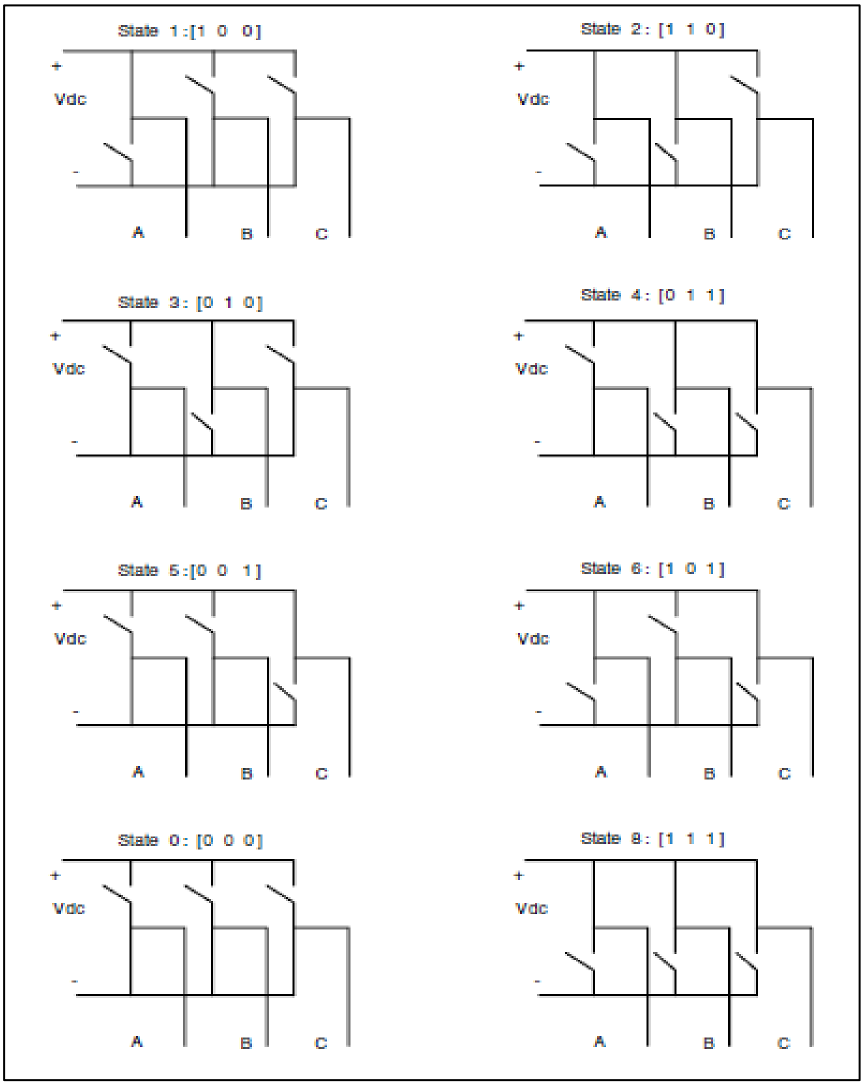


Figure 3.2: Possible switching states of three-phase VSI [14].

The phase to neutral voltage quantities are obtained from:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{V_i}{3} * \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3.1}$$

The phase to phase voltages are:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_i * \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{3.2}$$

The next table shows the output voltage for each state of the switches.

Table 3.1: Switching vectors, phase voltages and output line to line voltages

Voltage Vectors	Switching Vectors			Line to Neutral Voltage			Line to Line Voltage		
	a	B	c	V_{an}/V_i	V_{bn}/V_i	V_{cn}/Vi	V_{ab}/V_i	V_{bc}/V_i	V_{ca}/V_i
V0	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V2	1	1	0	1/3	1/3	-2/3	0	1	-1
V3	0	1	0	-1/3	2/3	-1/3	-1	0	0
V4	0	1	1	-2/3	1/3	1/3	-1	1	1
V5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	
V7	1	1	1	0	0	0	0	0	0

Table 3.2: Stator-Voltages in (α-β) frame and related voltage vector.

Voltage Vectors	V_{α}	V_{β}
V0	0	0
V1	$2V_{dc}/3$	0
V2	$V_{dc}/3$	$V_{dc}/\sqrt{3}$
V3	$-1V_{dc}/3$	$-V_{dc}/\sqrt{3}$
V4	$-2V_{dc}/3$	0
V5	$-V_{dc}/3$	$-V_{dc}/\sqrt{3}$
V6	$V_{dc}/3$	$-V_{dc}/\sqrt{3}$
V7	0	0

3.2.2. Space Vector Modulation Technique

The voltage source inverter explained before can be controlled since it is constructed using electronic switches. The purpose of this control is to optimize the elimination of total harmonic distortion (THD) using Pulse Width Modulation (PWM) technique.

There are many possible PWM techniques proposed in the literature. The classification of the PWM techniques can be given as follows:

- Sinusoidal PWM (SPWM)
- Selected harmonic elimination PWM
- Minimum ripple current PWM
- Space vector PWM (SVM)
- Random PWM
- Hysteresis band current control PWM
- Sinusoidal PWM with instantaneous current controller
- Delta modulation
- Sigma-delta modulation.

Often, PWM techniques are classified on the basis of voltage or current control, feedforward or feedback methods, carrier or non-carrier-based control, etc [16].

In this section, we will review the principle of the SVM technique.

The space-vector PWM (SVM) method is an advanced, computation-intensive PWM method and is possibly the best among all the PWM techniques for variable-frequency drive applications. Because of its superior performance characteristics, it has been finding widespread application in recent years [16].

The objective of space vector PWM technique is to approximate the reference voltage vector Vref using the eight switching patterns. One simple method of approximation is to generate the average output of the inverter in a small period, T to be the same as that of Vref in the same period.

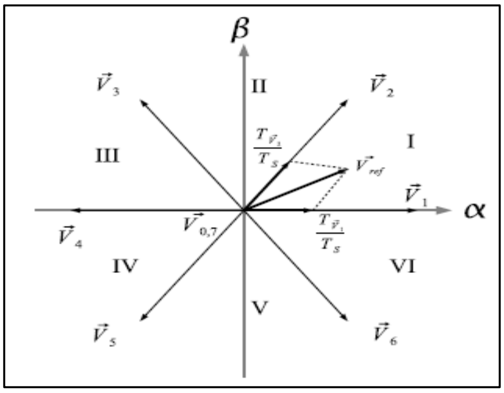


Figure3.3: Voltage vectors and sectors in αβ frame.

Therefore, the SVM can be implemented following a set of steps:

- ***Step 1: determine V_α, V_β, Vref and the angle θ***

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3.3)$$

$$|Vref| = \sqrt{V_\alpha^2 + V_\beta^2} \quad (3.4)$$

$$\theta = \tan^{-1}(\frac{V_\beta}{V_\alpha}) \quad (3.5)$$

- ***Step2: determine the time duration***

$$T_{Vk} = C * (sin\frac{k\pi}{3} * cos\theta - cos\frac{k\pi}{3} * sin\theta) \quad (3.6)$$

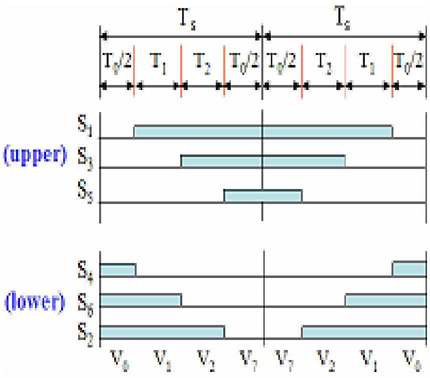
$$T_{Vk+1} = C * (-cos\theta * sin\frac{k-1}{3} * \pi + sin\theta * cos\frac{k-1}{3}\pi) \quad (3.7)$$

$$T_{V0,V7} = Ts - T_{Vk} - T_{Vk+1} \quad (3.8)$$

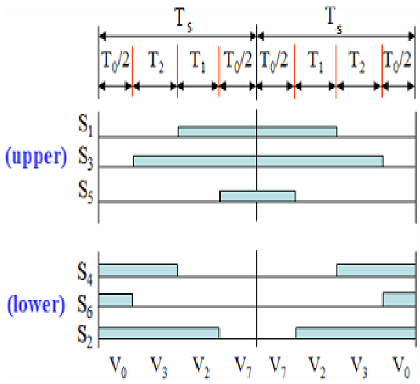
$$C = \frac{\sqrt{3} * |Vref| * Ts}{Vi} \quad (3.9)$$

$$0 \leq \theta \leq \frac{\pi}{3} \quad (3.10)$$

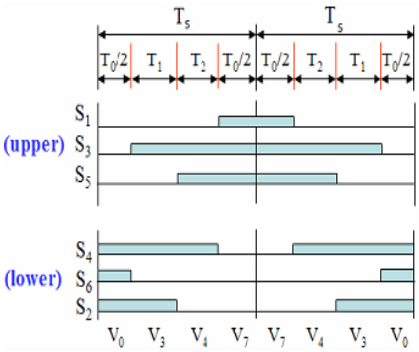
- ***Step3: determine the switching time for each switch***



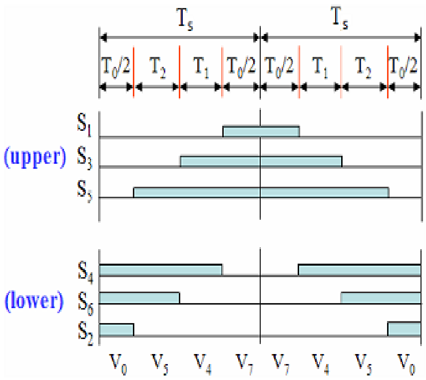
a. *Sector 1*



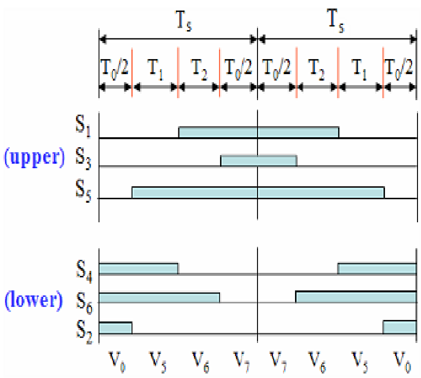
b. Sector 2



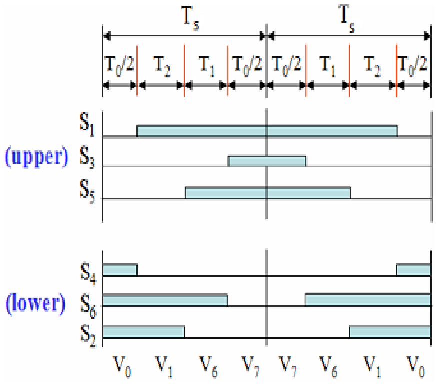
c. Sector 3



d. Sector 4



e. Sector 5



f. Sector 6

Figure 3.4: Space Vector PWM switching patterns at each sector.

Based on the previous figure, a table is generated to summarize the switching time at each sector for a period Ts.

Table 3.3 Switching time calculation at each sector.

Sector k	Upper switches	Lower switches
1	S1=T1+T2+T0/2 S3=T1+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=T0/2+T2 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+T2+T0/2 S5=T1+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

3.2.3. Direct Torque Control Space Vector Modulation (DTC-SVM)

The main advantages of this control technique are achieving a constant switching frequency and reducing torque and flux ripples.

From the torque equation of the motor:

$$T_e = \frac{3}{2} * \frac{P}{2} * \frac{\lambda m * |\lambda s| * \sin\delta}{L} \quad (3.11)$$

We can notice that the torque control can be done by varying the angle δ where δ is the angle between stator and rotor flux linkage.

It exists different structures and algorithms for implementing DTC-SVM, cascade structure, parallel structure, with or without speed control loop.

In our case, we have chosen to apply the parallel structure with speed control loop.

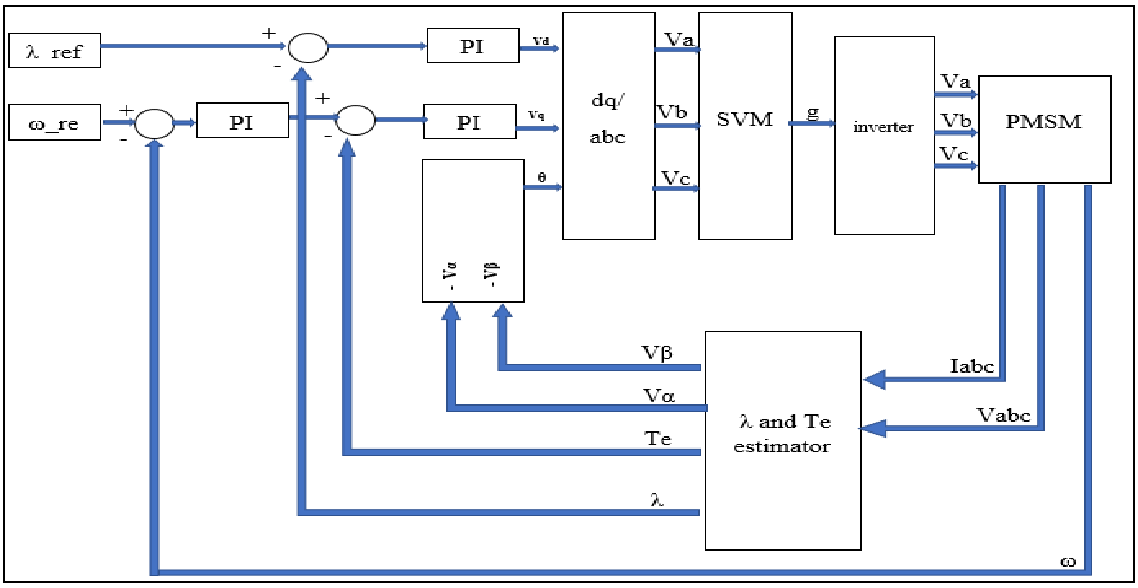


Figure 3.5: Block diagram of parallel structure DTC-SVM with speed control loop.

For the flux control loop, we set the reference flux and compare it with the flux generated inside the machine. The flux error is put in the PI controller to generate voltage V_d. The other loop, we set the speed reference and compare it with the actual speed of the motor. The speed error signal is put inside the PI and get the reference torque controlled by the PI again to get V_q. Including the flux angle θ, the application of inverse Park transforms to generate the three phase voltages as input for the input of the SVM. The latter generates a control signal that choses the appropriate switching states of the inverter to feed the PMSM.

3.3. Conclusion

The previous part was about the theoretical part of the DTC SVM, where the operating steps of the VSI controlled by SVM were introduced. Besides, we explained the control scheme of DTC SVM that has been chosen for implementation in this thesis. The next chapter will show the steps and the results of our implementation.

4.1. Introduction

So far, we have seen the theoretical basics of the SVM and the DTC SVM. This chapter deals with analysis of the simulation results of the DTC SVM for a PMSM.

4.1. Simulation model of the VSI controlled by SVM

The SVM circuit presented in the figure 4.1. and 4.2. was simulated in MATLAB/Simulink software. The proposed model consists of the SVM block and a voltage source inverter.

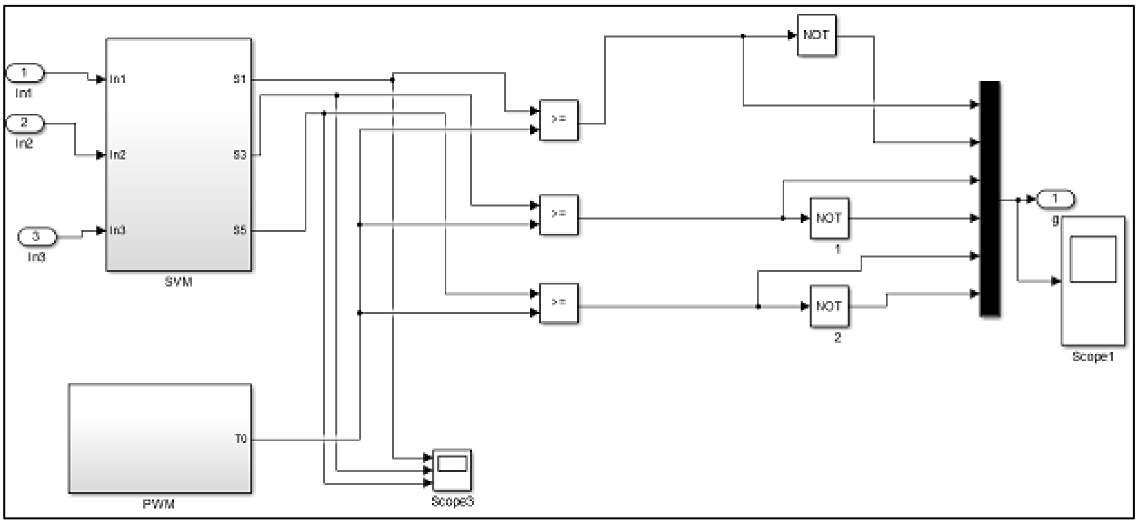


Figure 4.1: SVM Simulink block

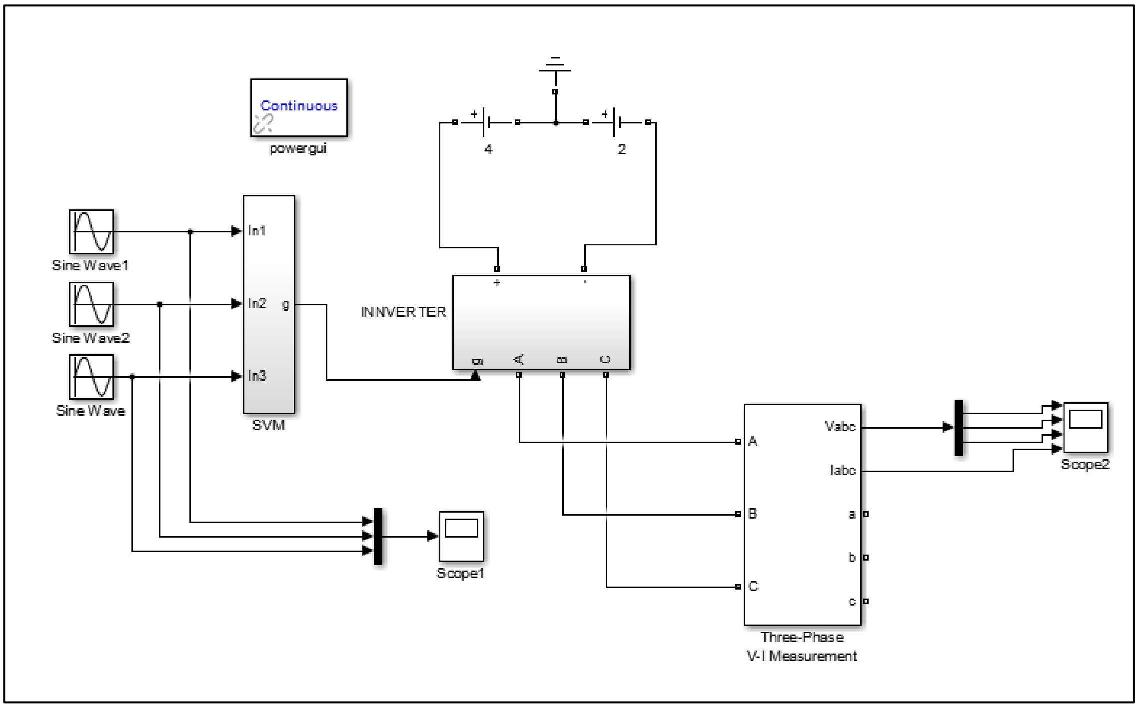


Figure 4.2: Inverter Controlled by SVM.

4.2. Simulation model of the DTC SVM inverter fed PMSM

The proposed scheme consists on speed controller and flux controller, the implemented circuit is shown in the following figure:

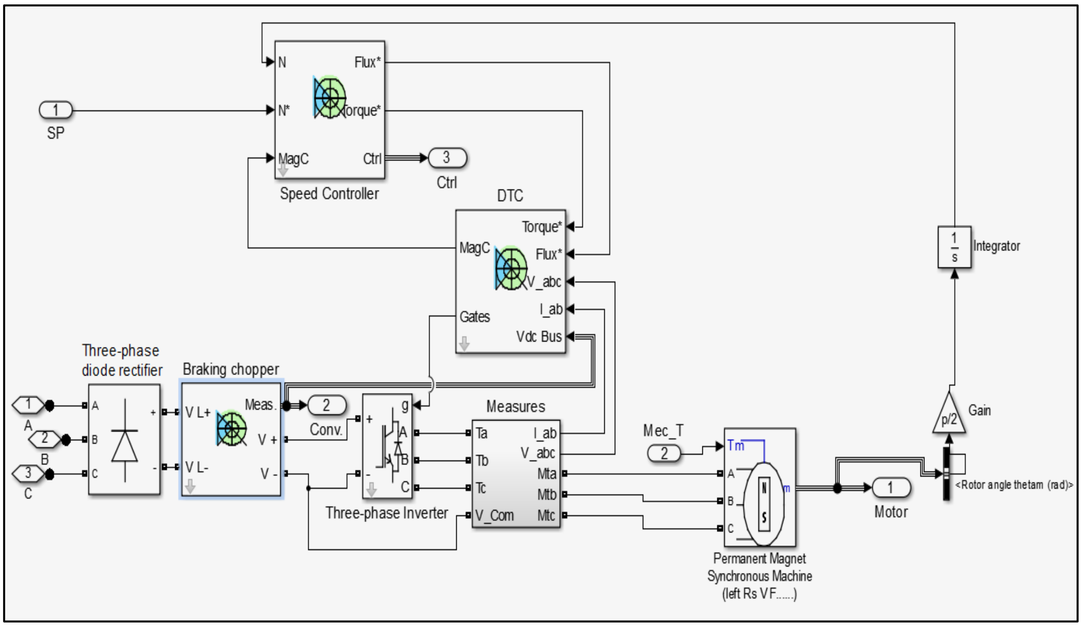


Figure 4.3: detailed block diagram of DTC SVM for PMSM

4.3. Results and Discussion

This figure 4.4.a. shows the Clarke's transformation in which V_α and V_β shifted by 90° and the angle separating them.

These quantities are used for duty cycle and reference voltage calculation.

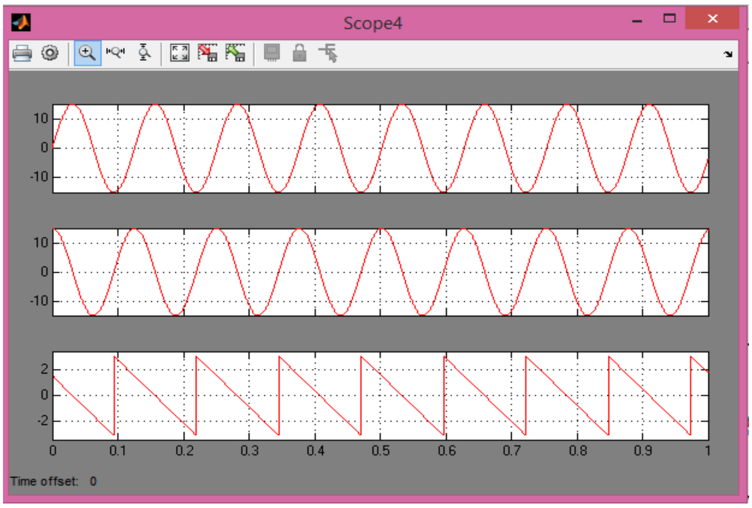


Figure 4.4: V_α , V_β and the angle separating them.

Figure 4.4.b. shows the output duty cycle of the SVM, where we it can be seen clearly that the states are shifted by 120°

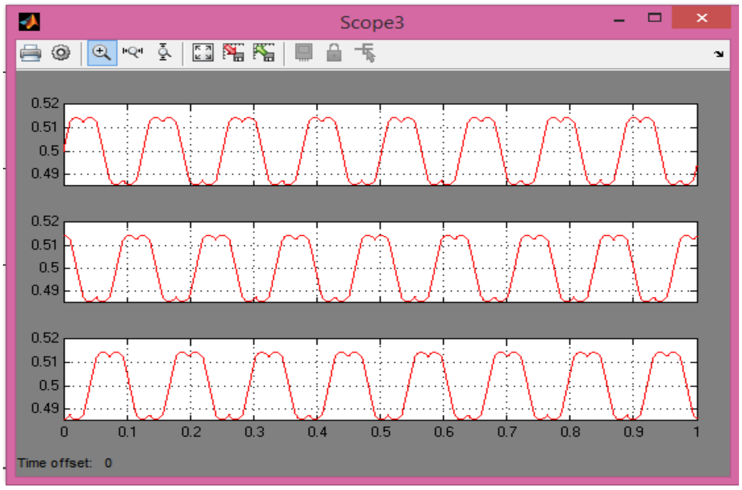


Figure 4.5: Output duty cycle

Figure 4.4.c. shows the phase to phase output voltages Vab, Vbc and Vca and phase currents.

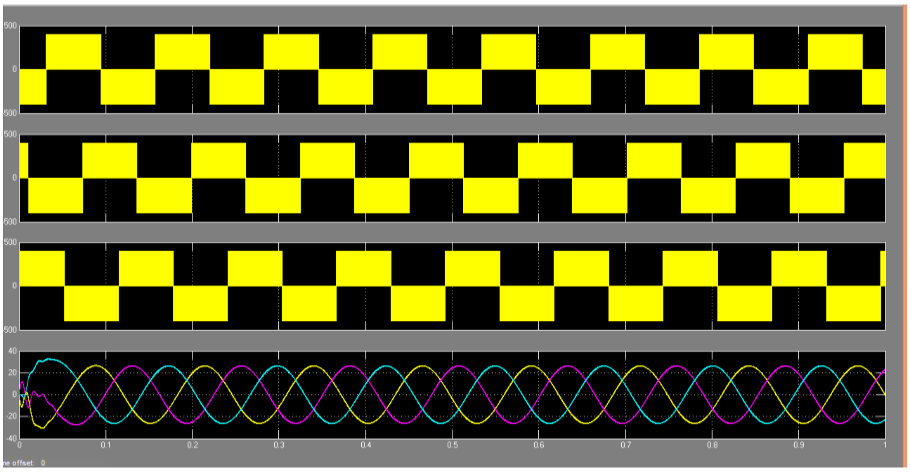


Figure 4.6: phase to phase voltages and phase currents.

The voltages follow a sinusoidal shape shifted by 120° that will be entered to the stator of the PMSM.

The currents are of a sinusoidal shape shifted by 120°.

The DTC SVM simulation gave the following outputs

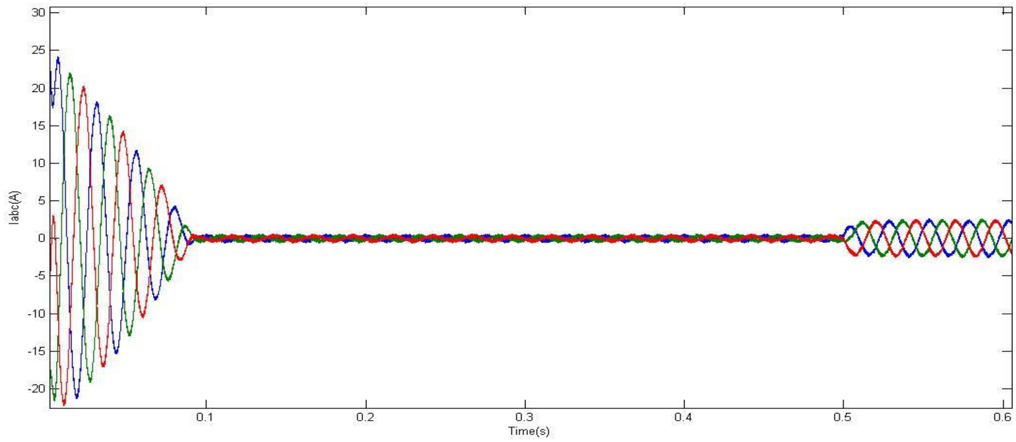


Figure 4.7: Phase stator current output.

The figure of the output current shows three parts where the first part is the transient part where the current is very high, the second where no load is applied and the last part a load is applied. The current is in sinusoidal shape where 120° phase shift has occurred between the phases.

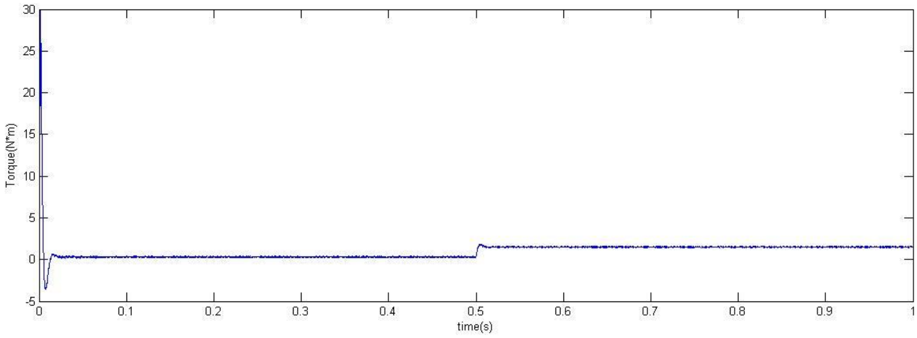


Figure 4.8: output torque.

The output torque is of a constant value. In transient time, the torque changes and at steady state with no load the torque goes to zero. Applying a load, the torque takes the value of the load torque.

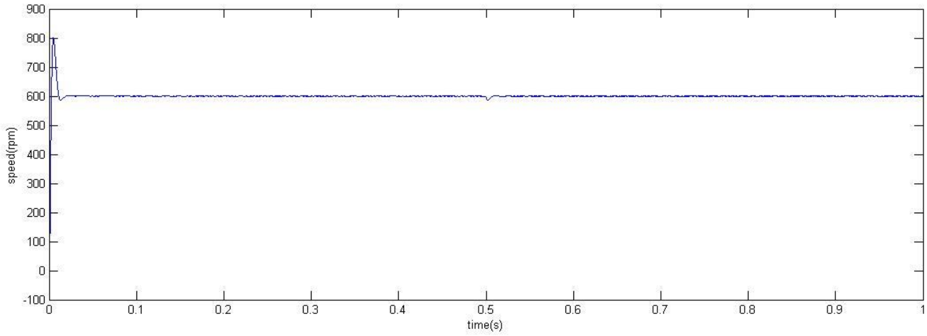


Figure 4.9: Output Speed.

The speed is of a constant value as the reference one.

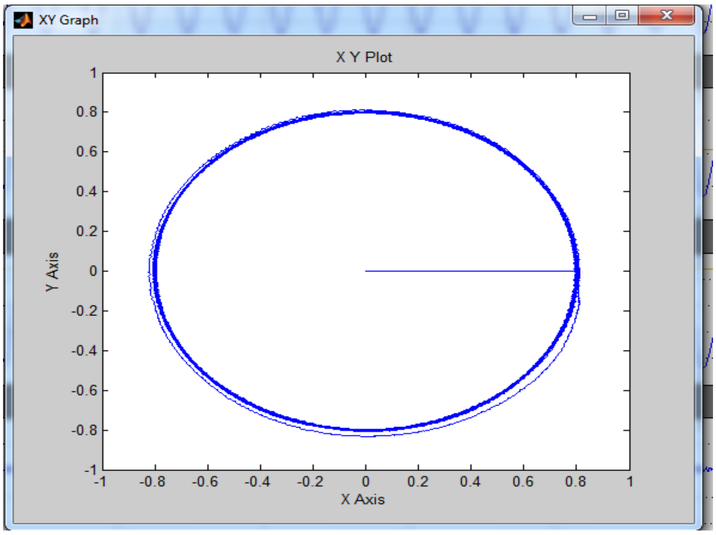


Figure 4.10: stator flux trajectory

4.4. Conclusion

In this chapter, the MATLAB /Simulink simulation of inverter controlled by SVM technique has been presented followed by the DTC SVM for a PMSM. The results of the simulation were analyzed. The SVM control gates were recorded and the response of the motor to the command algorithm was good. The circular flux trajectory devoted a decrease in harmonics for the system that could be noticed in the sinusoidal output current.

5.1. Introduction

This chapter is devoted for the experimental realization of the SVM technique. A general description of the experiment is shown and the presentation of the main equipements and the test banch of the experiment. The results of the experiment are presented followed by the analysis and synthesis and the concluding points.

5.2. General procedure of the implementation

The implementation procedure was divided into three main steps. The first is to upload the Matlab program to the DSP card and visulaze the output PWM signals that would be filtered using a low pass filter.

The next step is to fire the IGBTs of the inverter using the output signal of the DSP that is passed through the Dspace interface with the SEMIKRON inverter module. The output signals are reported.

5.3. Description of the test bench

a. **IGBT Power Electronics Teaching System Principle for sizing power converters**

The SEMITEACH is a 20KV setup with a diode bridge rectifier, a three-phase IGBT inverter and an IGBT chopper. The module is equipped with the IGBT drivers, a fan for cooling the system, a DC link capacitor, the heat sink temperature measurement sensor and a protective thermal switch. The circuit diagram of the module is shown in the following figure.

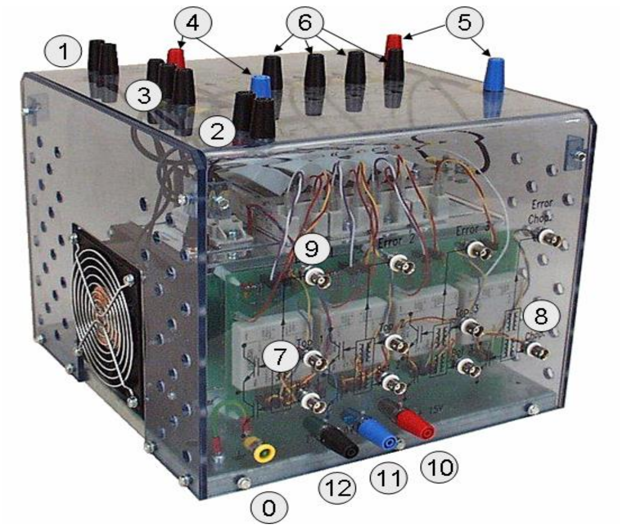


Figure 5.1: SEMITEACH inverter module [17].

The description of the device is given in the following table

Table 5.1: Description of the SEMITEACH inverter module [17].

N°	type	function	voltage level	max current level
0	Grounding panel socket	Earth connection	0V	30 A
1	Banana connector 4mm	Fan power supply	230V/50Hz	1 A
2	Banana connector 4mm	Thermal trip	15V	5 A
3	Banana connector 4mm	Rectifier input	230 / 400V	30 A
4	Banana connector 4mm	DC rectifier outputs	600 VDC (Red is positive, Blue is negative)	30 A
5	Banana connector 4mm	DC IGBT inverter inputs	600 VDC (Red is positive, Blue is negative)	30 A
6	Banana connector 4mm	AC IGBT inverter	400 VAC / 600 VDC	30 A

		+chopper outputs		
7	BNC coaxial insulated, 50 Ω	PWM input of inverter	C-MOS logic 0/15 V (shield is internally connected to driver's 0V), 0V =open IGBT ,15 V = closed IGBT	1 A
8	BNC coaxial insulated, 50 Ω	PWM input of brake chopper	C-MOS logic 0/15V (shield is internally connected driver's 0V), 0V =open IGBT, 15 V = closed IGBT	1 A
9	BNC coaxial insulated, 50 Ω	Error output	C-MOS logic 0/15V (shield is internally connected to driver's 0V)	1 A
10	Banana connector 4mm	15V driver power supply	15V	5 A
11	Banana connector 4mm	0V driver power supply	15V	5 A
12	Banana connector 4mm	Temperature sensor	0-5V	1 A

b. Digital Signal Processor TMS320f2802x

A Digital Signal Processor, or DSP, is a specialized microprocessor that has an architecture which is optimized for the fast-operational needs of digital signal processing. A Digital Signal Processor (DSP) can process data in real time, making it ideal for applications that can't tolerate delays [18].

DSP also provides high speed high resolution, sensor less algorithm, low power, single power supply and small packaging in order to reduce the system cost.

The F2802x Piccolo™ family of microcontrollers provides the power of the C28x core coupled with highly integrated control peripherals in low pin-count devices. This family is code-compatible with previous C28xbased code, and also provides a high level of analog integration [19].

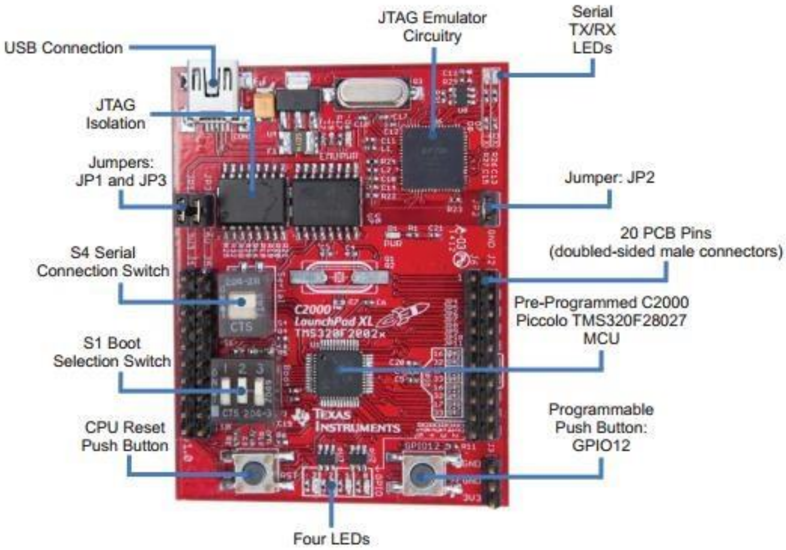


Figure 5.2: DSP C2000 launchpad [20].

c. Isolation and adaptation interface

The isolation and adaptation interface is a device that allows to the user to convert the control signals to SEMIKRON inverters to generate the three phase output from the inverter to feed the motor. It converts the 3.3V output from the DSP to 15V output.

Figure 5.3: µTECH interface.

5.4. experimental results

The Matlab simulation circuit is presented in the following figure

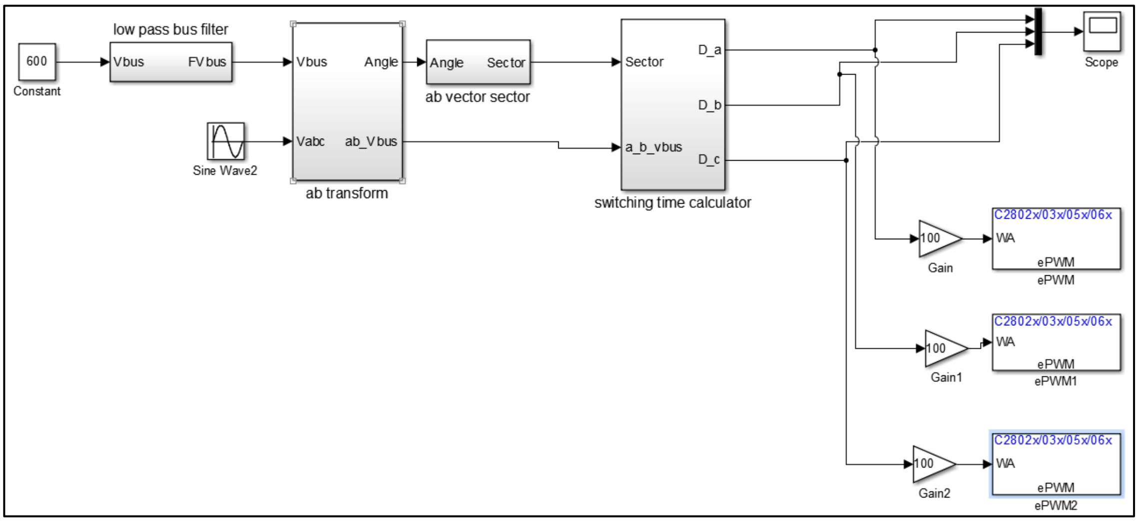


Figure 5.4: circuit implemented on MATLAB/Simulink

The output swithcing pulses generated from the SVM in Matlab

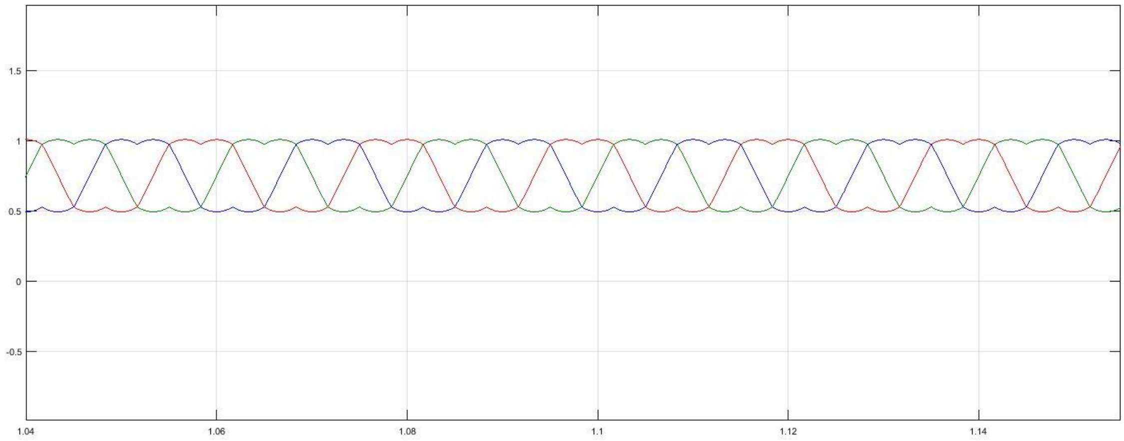


Figure 5.5: output switching signal from matlab to DSP.

The signals are shifted by 120°

Uploading the program to the DSP and filtering the signal using a low pass filter

As shown in the figure:

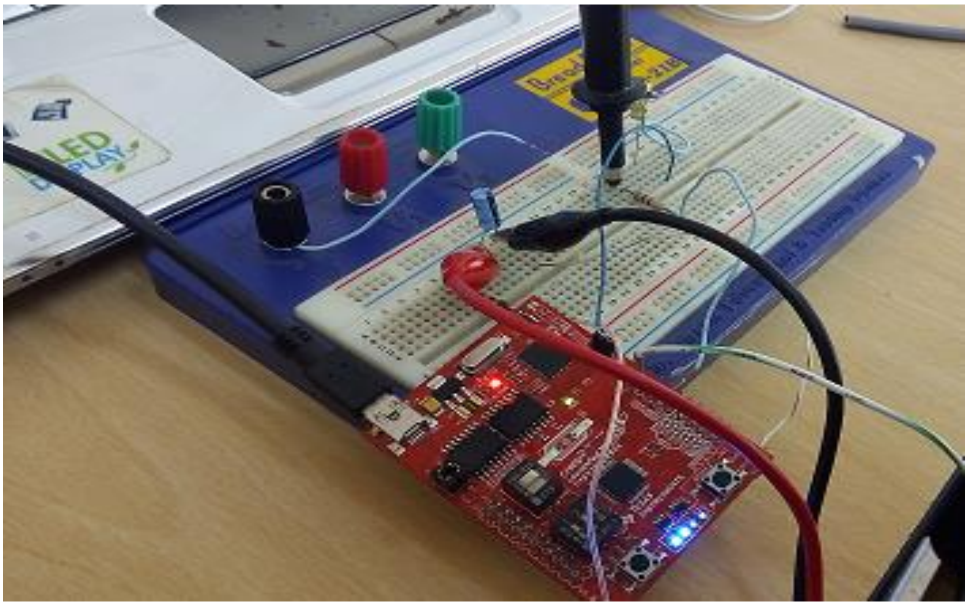


Figure 5.6: circuit showing the DSP pins connected to a filter.

For the low pass filter, we have used a capacitance of 10μF and a resistance of 10k in order to visualize the output signal from the DSP.

The output from the DSP pins

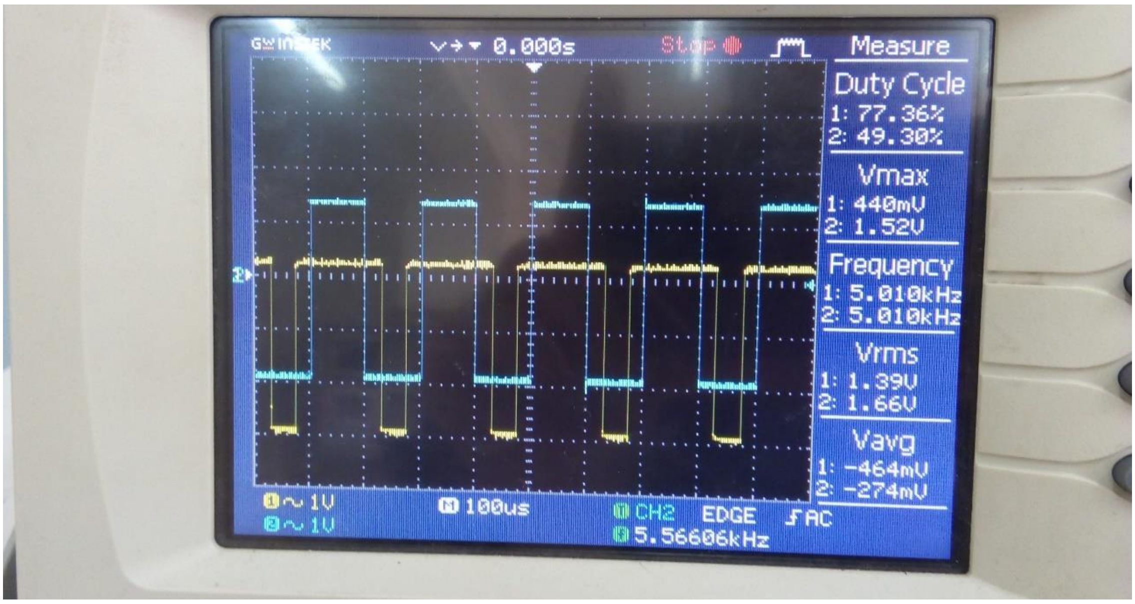


Figure 5.7: PWM output signal from pins 1 and 2.

Then, the signal was filtered to obtain a sinusoidal output and the result is shown in the figure

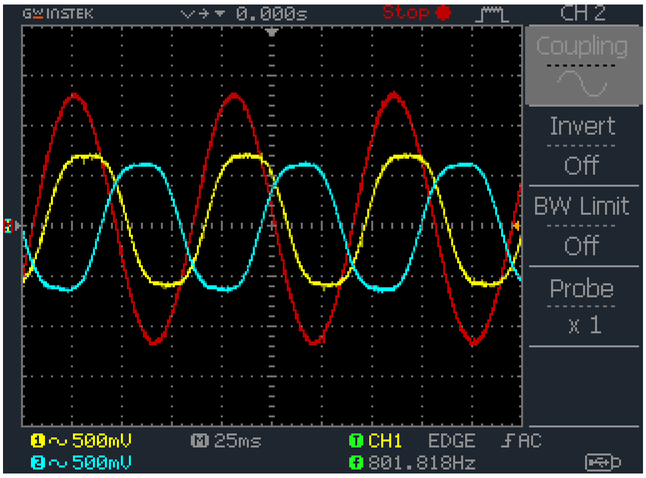
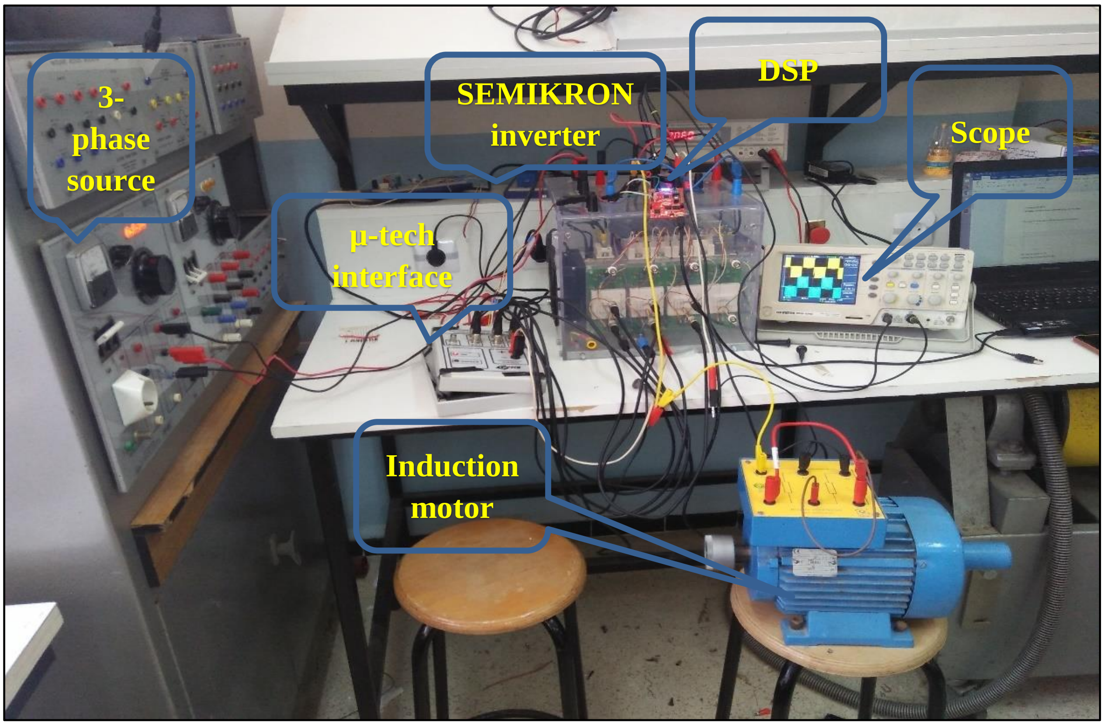


Figure 5.8: output switching states from the filtered output of the DSP.

The final circuit that is implemented is shown in figure (5.9). The output of the DTC is put into the interface of DSP card to control the SEMIKRON inverter gates.

The input of the rectifier is taken from the three-phase generator. The output DC signal is given as input for the inverter circuit. The output from the inverter is taken directly to the three-phase of the motor.



Figures 5.9: Output SVM from inverter phase to neutral plus phase to phase.

Outputs recorded from the motor

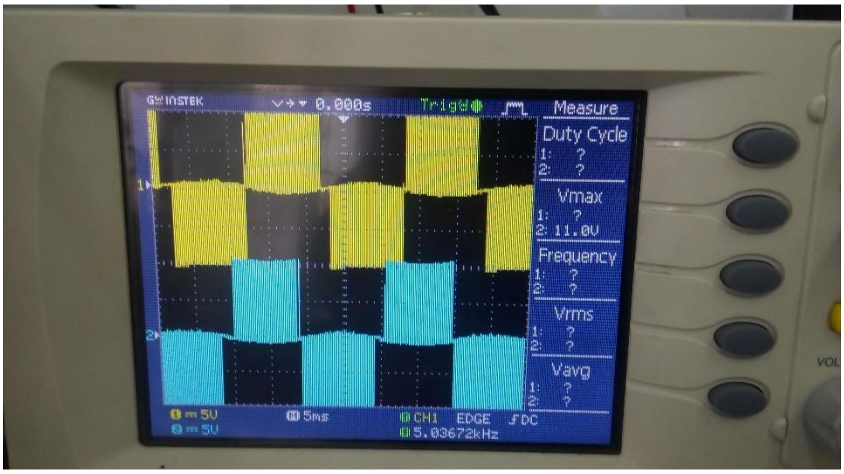


Figure 5.10: phase to phase output voltage from the inverter.

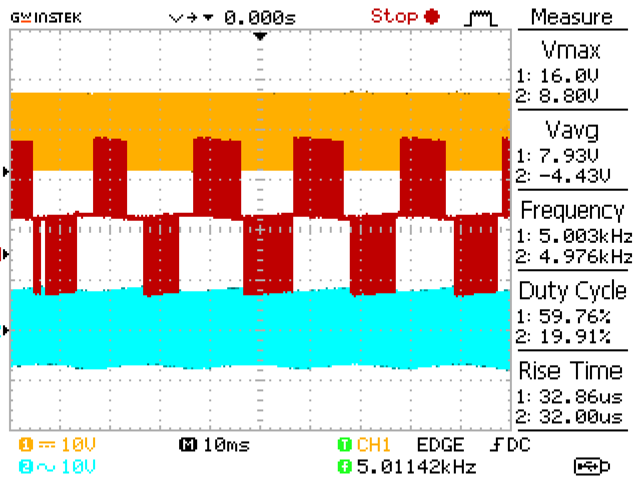


Figure 5.11: Output switching gates.

The previous figure shows the signal taken from the output of the interface. It shows the control signal of the inverter where the yellow and blue signals are phase control signals and the red one is the phase to phase signal.

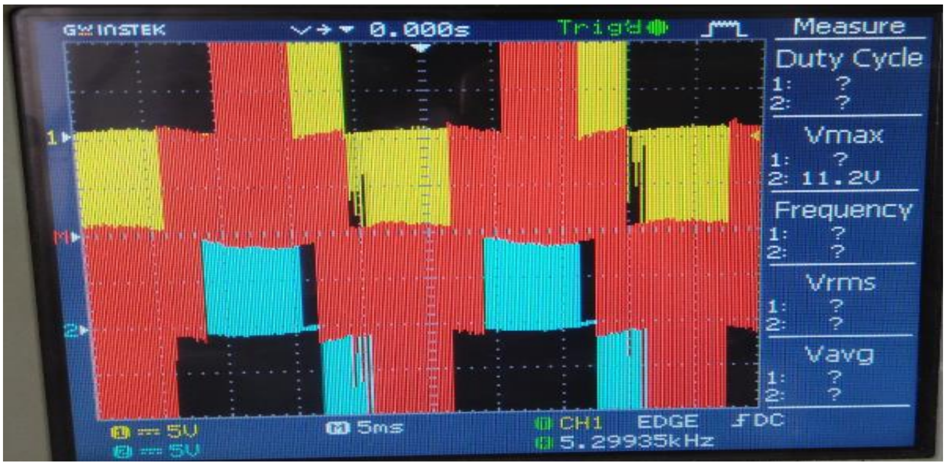


Figure 5.12: Phase voltage in red.

The three-phase current from the motor is recorded

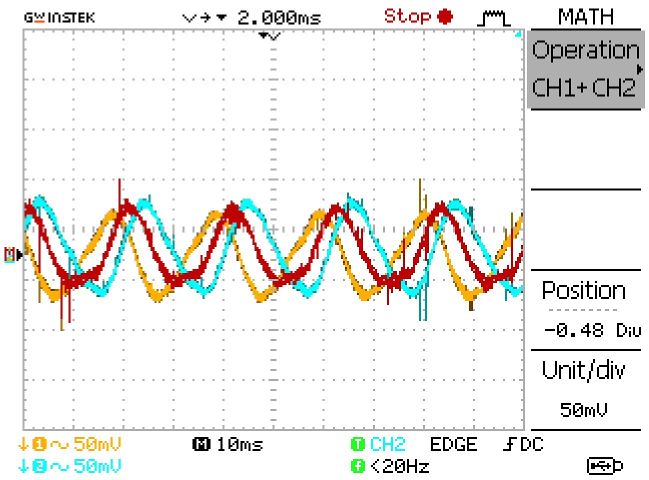


Figure 5.13: three-phase motor currents.

The output currents from the motor are of sinusoidal shape with 120° phase shift. The currents have low harmonics due to the SVM method that has a constant switching frequency.

5.5. Discussion

The results that were found from the implementation show the switching signals from SVM to control the inverter. The response of the motor shows a sinusoidal output current with less harmonics and small vibrations.

The SVM method is a suitable technique for various controls of the AC machines.

5.6. Conclusion

This experiment described the general procedure of the implementation of DSP based SVM controlled inverter feeding an AC motor.

The different components of the experiment were introduced as well as the arrangement of the whole system in the laboratory.

The control of switching states of the inverter generated from the SVM were analyzed.

General Conclusion

This thesis studied the Direct Torque Control with Space Vector Modulation control technique of inverter fed PMSM. This method should provide less harmonics and robust starting. The proposed scheme was simple where the reference vector was calculated from the flux and torque estimator.

Furthermore, experimental tests were done by implementing the SVM algorithm on the DSP card to control the switches of the inverter.
The isolation and adaptation interface with SEMIKRON inverter from µTECH had to be modified to be used as interface between DSP and the inverter module.

The results of the implementation as the switching states, the line to line voltages were compared and confirmed from those of simulation.
The main achievement of this implementation is the constant switching frequency that has been imposed in the SVM algorithm and that provided a good steady state response of the current in the AC machine with less harmonics and less noise when operating.

Future work

Although this thesis has achieved many results, but it still some points to be developed:

- Variable frequency and variable amplitude sinusoidal input for the SVM in order to see the variation of the output by varying the variables mentioned previously.
- Implement the flux and torque estimator to achieve the DTC SVM control.

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