# DIRECT TORQUE CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

**Thesis submitted to**

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**In Partial Fulfilment of the Requirements for the Degree of**

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***Submitted by***

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## National Institute of Technology Rourkela

# CERTIFICATE

This is to certify that the thesis entitled, ***'Direct Torque Control of Permanent Magnet Synchronous Motor'*** Submitted by **Anwesha Panda (110EE0215)** in partial fulfilment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at the National Institute Of Technology, Rourkela is a bonafide and authentic research work carried out by her under my supervision and guidance over the last one year (2013-14).

To the best of my knowledge, the work embodied in this thesis has not been submitted earlier, in part or full, to any other university or institution for the award of any Degree or Diploma.

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Date:

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# ABSTRACT


Permanent Magnet Synchronous Motors (PMSM's) are used in places that require fast torque response and high-performance operation of the machine. The Direct Torque Control (DTC) technique is different from methods which use current controllers in an proper reference frame to control the motor torque and fluxe values. The DTC technique does not any current controllers. DTC controls the Voltage source Inverter states on the basis of difference between the required and obtained torque and flux values. This is done by selecting one out of the six voltage vectors obtained by the Inverter (VSI) to have torque and flux fluctuations in between the limits of 2 hysteresis bands.

This thesis obtains the modelling of the Direct Torque Control (DTC) system of PMSM using MATLAB/Simulink®. Speed control of PMSM using Field Oriented Control technique and Direct Torque Space Vector Pulse Width Modulation technique is also analysed and compared with traditional DTC. Simulation results are presented to help analyse the system performance and PI controller parameters influence on the system performance. The analysis is also done with fuzzy logic controller.



*Index Terms*—Direct torque control, permanent magnet synchronous motor, hysteresis loop, sensorless control, stator flux linkage, Voltage source Inverter, SV-PWM Control.

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# LIST OF SYMBOLS

| | |
|---|---|
| $u_q$ | : Quadrature axis Voltage |
| $u_d$ | : Direct Axis Voltage |
| $R_s$ | : Stator Resistance |
| $i_q$ | : Current in Quadrature Axis |
| $i_d$ | : Current in Direct Axis |
| $L_q$ | : Quadrature Axis Stator Inductance |
| $L_d$ | : Direct Axis Stator Inductance |
| $p$ | : $\frac{d}{dt}$, differential operator |
| $\Psi_q$ | : Quadrature Axis Stator Flux Linkage |
| $\Psi_d$ | : Direct Axis Stator Flux Linkage |
| $\Psi_f$ | : Permanent Magnet Flux Linkage |
| $\omega_r$ | : Rotor Speed in electrical |
| $\omega_m$ | : Rotor Speed in Mechanical |
| $n_p$ | : No. of Poles |
| $T_e$ | : Electromagnetic Torque |
| $T_L$ | : Load Torque |
| B | : Friction Coefficient |
| J | : Inertia of PMSM drive |

# Chapter 1

# Introduction

## 1.1 Introduction

Since the last three decades AC machine drives are becoming more popular, especially Induction Motor (IM) and Permanent Magnet Synchronous Motor, but with some special characteristics, the PMSM drives are ready to meet up sophisticated needs such as fast dynamic response, high power factor, and wide operating speed range, as a result, a gradual gain in the use of PMSM drives will surely be witness in the future in low and mid power applications.

In a PMSM, the dc field winding of the rotor is replaced by a permanent magnet to produce the air-gap magnetic flux. Having the magnets on the rotor, electrical losses due to field winding of the machine get reduced and the lack of the field losses improves the thermal characteristics of the PM machines and its efficiency. Absence of mechanical components like brushes and slip rings makes the motor lighter, high power to weight ratio for which a higher efficiency and reliability is achieved.

Because of the advantages, permanent magnet synchronous generator is preferred in wind turbine applications. Disadvantages of PM machines are: at high temperature, demagnetization of the magnet, manufacturing difficulties and high cost of PM material.

PM electric machines are classified into 2 types: PMDC machines and PMAC machines. PMDC machines are like the DC commutator machines; with the field winding being replaced by the permanent magnets. In PMAC the field is generated by the permanent magnets placed on the rotor and the sliprings, the brushes and the commutator does not exist. That is why PMAC is simpler to use instead of PMDC.PMAC is divided into two type depending on the nature of the back electromotive force (EMF): Trapezoidal type and Sinusoidal type. Sinusoidal type PMAC machine can be further divided as Surface mounted PMSM and Interior PMSM.

The trapezoidal PMAC machines also called Brushless DC motors (BLDC and build up trapezoidal back EMF waveforms with following characteristics:

1. Rectangular distribution of magnet flux in the air gap
2. Rectangular current waveform

3. Concentrated stator windings.

The sinusoidal PMAC machines are called Permanent magnet synchronous machines (PMSM) and build up sinusoidal back EMF waveforms with following characteristics:

1. Sinusoidal current waveforms
2. Sinusoidal distribution of stator conductors.
3. Sinusoidal distribution of magnet flux in the air gap

Based on the rotor configuration the PM synchronous machine can be classified as:

**(a) Surface mounted magnet type (SPMSM):**

In this case the magnets are mounted on the surface of the rotor. The magnets can be considered as air because the permeability of the magnets is nearly unity and there is no saliency because of same width of the magnets. Therefore the inductances expressed in the quadrature coordinates are equal ($L_d = L_q$).

**(b) Interior magnet type (IPMSM)**

Here the magnets are place inside the rotor. In this configuration saliency is presented and the d-axis air-gap is greater compared with the q axis air gap for which the q axis inductance is greater in value than the d axis inductance

### 1.2 Research background

PM motor drives have been an area of interest for the past thirty years. Different researcher have carried out modelling, analysis and simulation of PMSM drives. This content offers a brief review of some of the published work on the PMSM drive system.

In the year 1986 Jahns, T.M., Kliman, G.B. and Neumann, T.W. [1] proposed that in IPMSM had special features for adjustable speed operation. The control principle of the sinusoidal currents in magnitude alongwith phase angle wrt the rotor direction was a path for achieving smooth response of torque control.

Extr-high energy magnets are used in IPM motor to improve the performance characteristics of the rotor. In this method Sebastian, T. Slemon, G. R. and Rahman, M. A. [2] in 1986, presented equivalent electric circuit models for these motors and compared estimated parameters with measured parameters.

Pillay and Krishnan, R. [3] in 1988, presented views on PM motor drives and classified them into two types. These are permanent magnet synchronous motor drives and brushless dc motor (BDCM) drives. The PMSM had a sinusoidal back emf and required sinusoidal stator currents which produced constant torque while the BDCM had a trapezoidal back emf, required rectangular stator currents for producing constant torque.

Further as an extension of his previous work Pillay and Krishnan, R. in 1989 [4] presented the vector control as well as complete modelling of the drive system in rotor reference frame except damper windings.

A torque production at low speeds along with the system practical limitation in the high speed regions were investigated by Dhaouadi R. and Mohan N. [5] by using ramp type, hysteresis type and space vector type controller and performances of these different types of controllers were noticed. Traditional Hysteresis control method is used due to its simplicity in implementation, fast control response, and inherent current(peak) limiting ability.

In the year of 2004, Jian-Xin, X., Panda, S. K., Ya-Jun, P., Tong Heng, L. and Lam, B. H. [6] applied a module approach to a PMSM control. Based on the functioning of the individual module, this enabled the powerfully intelligent and robust control modules to easily replace any existing module.

Hoang Le-Huy [7] obtained an unique approach of simulation of drives using state-space formula in Simulink. This method has been successfully included in a simulation package called "Power System Block set" (PSB) for use in MATLAB/Simulink software.

B. K. Bose [8] offered a different type of synchronous motors. All the equations were derived in synchronously rotating frame of reference and was given in the matrix form. The equivalent circuit was expressed with the presence of the damper windings and the permanent magnet was assumed to be a constant current source.

The fuzzy logic based speed control of an interior permanent synchronous motor (IPMSM) drive was presented by M. N. Uddin and M. A. Rahman [9] in 1999. The fundamentals of fuzzy logic algorithms related to motor control applications were explained. A new fuzzy speed control algorithm for IPMSM drive has been designed.

Zhonghui Zhang, Jiao Shu simulated the field oriented vector control of PMSM drive using current reference tracking and PWM inverter switching.[10]This work used conventional PI controller for tracking purpose. B.Adhavan, A. Kuppuswamy, G.Jayabaskaran and Dr.V.Jagannathan used fuzzy logic controller instead of PI for the same and did performance comparison analysis of both the types of controller.[11]

Zhuqiang Lu, Honggang Sheng, Herbert L. Hess, Kevin M. Buck applied principle of direct torque control to the PMSM drive system. This method directly controlled the speed of drive by estimating the torque and flux linkage value and selecting the appropriate switching vector from the look-up table without any kind of mechanical sensor.[12]

Chen ming, Gao Ranying, Song Rongming presented technique of direct control of PMSM using space vector pulse width modulation of the inverter gating pulses. It emphasised on the how this method of controlling speed had advantage over the traditional control. Rotor mechanical position sensor was required for the estimation of torque and flux linkage vector.[13]

### 1.3 Motivation

Comprising with above mentioned many special characteristics of PMSM is the present day researcher's hotspot. It can be operated at improved power factor for which the overall system power factor is improved. PMSM drive could become an emerging competitor to the IM drive in servo like industrial applications.

There is a great challenge to improve the performance with accurate speed tracking and smooth torque output minimizing its ripple during transient. Mechanical sensors are lossy and bulky. The DTC can achieve speed control without requiring any mechanical sensors. Hence this scheme has high influence on drive system.

### 1.4 Objective

The main objective of this research-work is to improve the performance of an PMSM drive by attending more precise speed tracking and smooth torque response by implementing a direct torque scheme.

The overall objectives to be achieved in this study are:

1. To design the equivalent d-q model of PMSM for its vector control analysis and closed loop operation of drive system.
2. Analysis and implementation of field oriented control, direct torque control, direct torque space vector modulation control in steady state and transient condition (step change in load and speed) in MATLAB/Simulink® environment.
3. To compare these control schemes performance relative to each other.

### 1.5 Organization of report

**Chapter1:** This describes briefly permanent magnet synchronous motor and it's direct toque control, the literature review done , motivation and objective of the work along with the organization of report.

**Chapter2:** In this chapter the modeling of the permanent magnet synchronous motor and equation describing it's characteristics is presented.

**Chapter3:**This chapter describes briefly the control methods available for the speed control of PMSM and thoroughly discuss the 3 control algorithms used for simulation purpose.

**Chapter4:** The simulation study is explained in this chapter.

**Chapter5:** This chapter presents the results and discussion of the simulation study.

**Chapter6:** Conclusion is presented in this chapter.

# Chapter 2

# The Mathematical Model of PMSM

## 2.1 Introduction

A three phase PMSM is constructed with sinusoidally distributed phase windings, with a 120 degree angle phase shift between the three windings. In a stator frame of reference coordinate system the phase vectors abc can be seen as they are fixed in angle, but with time varying amplitudes. This three vector representation makes calculation of machine parameters unnecessarily complex. Transformation of the system into a two vector orthogonal system, makes the necessary calculations much simpler.

## 2.2 Transformations[12]

A 3-phase machine can be described by a set of differential equations in time dependent coefficients. By the transformation of the motor parameters, the complexity of machine calculations can be reduced. According to the definitions the transforms give a 3rd component, zero-sequence. But since a motor normally is a balanced load, the zero-sequence not of importance.

The two transformations presented below are not the exact Clarke and Park, but in a slightly modified form to make power invariance.

### 2.2.1 Clarke's Transformation

The Clarke transformation changes a 3-phase system into a 2-phase system with orthogonal axes in the same stationary reference frame. The ABC parameters are transformed into αβ0 parameters by equation and in reverse by it’s inverse equation.

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \frac{2}{3} * \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{2.1}$$

### 2.2.2 Park's Transformation

The Park transformation changes a 2-phase system in one stationary reference frame into a 2-phase system with orthogonal axes in a different rotating reference frame. The 2 new phase variables are denoted d and q, and are referred to as the motors direct and quadrature-axis.

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} * \begin{bmatrix} X_d \\ X_q \end{bmatrix} \tag{2.2}$$

Where : $x_a$, $x_b$, $x_c$ are *abc* coordinates variables, $x_\alpha$, $x_\beta$ are α−β coordinates variables, $x_d$ ,$x_q$ are the d-q coordinate variables and θ is the angle between *d* axis and *q* axis.[12]

$$X_{sr} = X_s e^{-i\theta_r} \tag{2.3}$$

$\Theta_r$ is the position angle between stator and rotor reference frame

## 2.3 The model

A surface-mounted SM is used in this research work, hence it's mathematical model of the PMSM is presented. The d-q model has been developed on rotor frame of reference. Stator mmf rotates at the same speed as that of the rotor.[12]

The model of PMSM without having damper winding has been developed on rotor reference frame using the following assumptions:[14]

1. The induced EMF is sinusoidal.
2. Eddy currents and hysteresis losses are negligible.
3. There are no field current dynamics.
4. The stator windings are balanced with sinusoidally distributed magneto-motive force (mmf).

.

The stator flux linkage, voltage, and electromagnetic torque equations in the *dq* reference frame are as follows:

$$\Psi_d = L_d i_d + \Psi_f \tag{2.4}$$

$$\Psi_q = L_q i_q \tag{2.5}$$

$$u_d = R_s i_d + {}^{d\Psi_d}/_{dt} - \omega_r \Psi_q \tag{2.6}$$

$$u_q = R_s i_q + {}^{d\Psi_q}/_{dt} + \omega_r \Psi_d \tag{2.7}$$

$$T_e = \frac{3}{2} n_p (\Psi_d i_q - \Psi_q i_d) \tag{2.8}$$

where $\Psi_{d,}$ $\Psi_q$ =Stator magnetic flux vector in dq frame and rotor magnetic flux vector : $\Psi_f$= stator back EMF constant

$L_d$ and $L_{q=}$ inductances

$\omega_r$ =Rotor Speed

$R_s$=Stator Resistance,

$n_p$=no. of poles

$i_d$,$i_q$=Stator current vector in dq frame,

$T_e$=Electro-magnetic torque developed and

$T_m$=Motor load torque.

The equation of dynamics of the motor:

$$T_e - T_m = J \, {}^{d\omega_r}/_{dt} + B\omega_r \tag{2.9}$$

In α−β coordinates, the stator flux linkage is expressed as

$$\Psi_\alpha = \int (u_\alpha - R_s i_\alpha) dt \tag{2.10}$$

$$\Psi_\beta = \int \left(u_\beta - R_s i_\beta\right) dt \tag{2.11}$$

Where $u_\alpha$, $u_\beta$, $i_\alpha$, $i_\beta$ are the voltages and currents in αβ axes, and $\varphi_\alpha$ and $\varphi_\beta$, are the stator flux linkages in αβ axes.

The torque expressions are given below .

$$T_e = \frac{3}{2} n_p (\Psi_\alpha i_\beta - \Psi_\beta i_\alpha) \tag{2.12}$$

$$T_e = \frac{3}{2} n_p (\Psi_s \times i_s) \tag{2.13}$$

$$T_e = \frac{3}{2} n_p (|\Psi_{s|} \times i_{sqc}) \tag{2.14}$$

## 2.4 Equivalent Circuit of Permanent Magnet Synchronous Motor

Equivalent circuits of the motor is used for simulation of motors. From the d-q modelling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived.

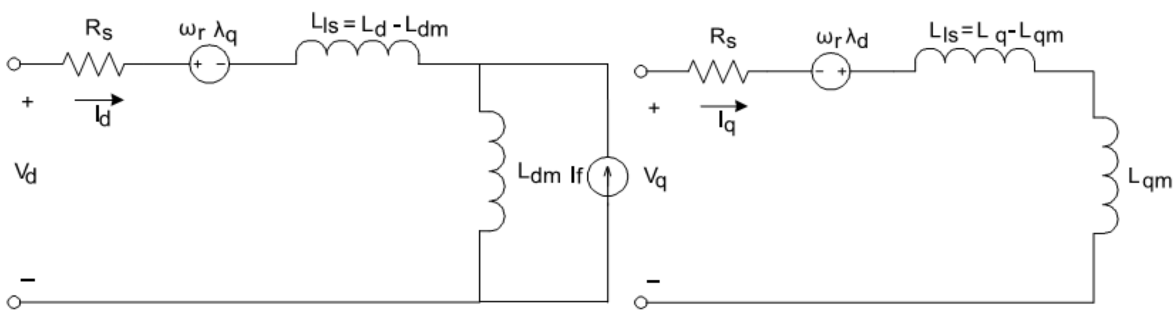


**Figure 2.1 Permanent Magnet Motor Electric Circuit without Damper Windings**

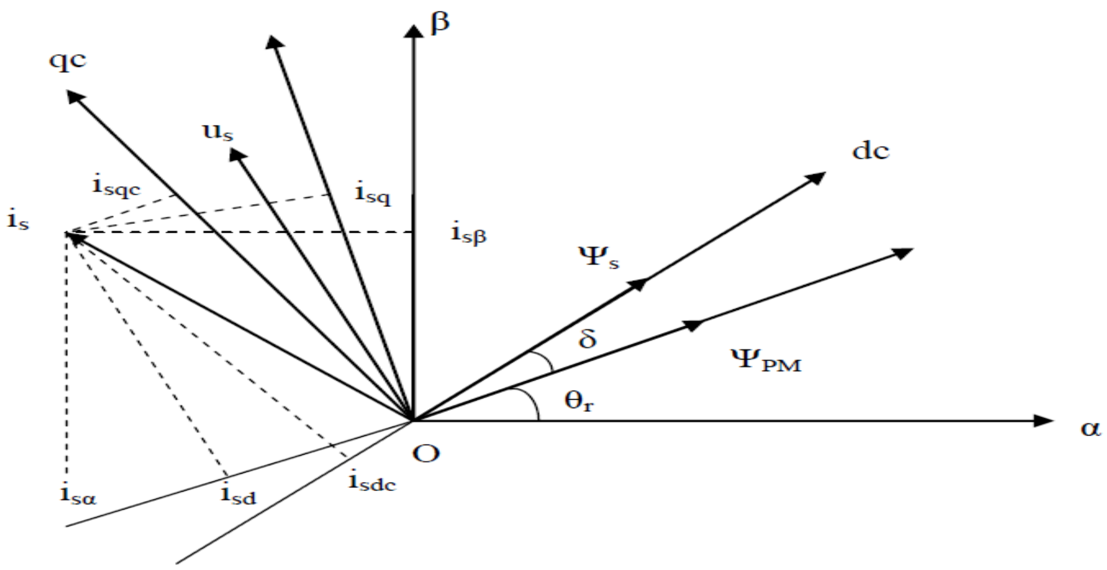


**Figure 2.2 Vector Diagram Of Different Reference Frame[13]**

# Chapter 3

# Control Systems of PMSM

### 3.1 Introduction

Synchronous motors are driven by the help of Variable Frequency Drive (VFD) for running at different speeds. Control methods of electric motors are divided into 2 major categories on the basis of what quantities they control.

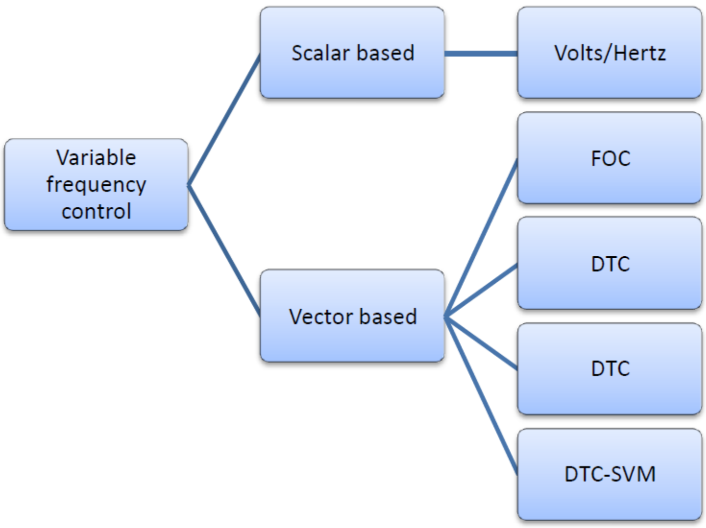


**Figure 3.1 Overview of available control strategies**

### 3.2 Scalar Control

It is based upon valid steady-state relations. Amplitude and frequency of the controlled variable are taken into account. It is used in places where several motors are driven in parallel by one inverter only.

1. Volts/Hertz Control:

   It is the simple kind of open loop control logic where the main idea is to keep stator flux constant at it's rated value.

### 3.3 Vector Control

Here in this case amplitude and position of the controlled space vector is considered. These relations are valid even in case of the transient conditions where along with magnitude of the stator and rotor flux angle between them is also taken into account.

1. Field Oriented Control

   Vector Control of currents & voltages which result in control of the space alignments of the electromagnetic fields.

2. Direct Torque Control

   The idea is to select voltage vector in accordance with the error between reference and actual torque and flux linkage value.

3. Direct Self Control

   This method is just like DTC but switching is lower.

4. DTC-Space Vector Modulation

   In DTC-SVM approach an estimator replaces the hysteresis comparators of DTC which calculates an voltage vector to compensate for the torque and flux error.

## Algorithm 1

### 3.4 Pmsm vector control theory

Vector control is actually control of phase and amplitude of the motor stator voltage / current vector at the same time. The motor torque is dependent upon the stator current $i_s = i_d + ji_q$. It is possible to control motor torque by $i_d$ and $i_q$. Current $i_d$ is for excitation. Hence we use $i_d = 0$ for the control strategy. Torque can be obtained only by the q axis current $i_q$. So let $i_d = 0$, through control the $i_q$, we are achieving maximum torque control in the s PMSM vector control. Figure 2shows a vector control strategy block diagram with the use of $i_d = 0$.[10]

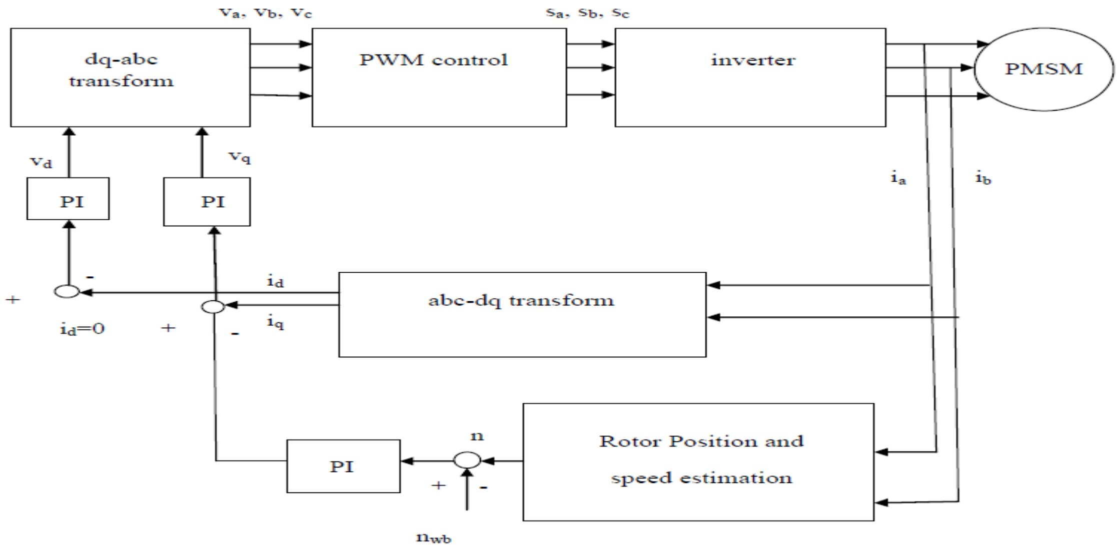


**Figure 3.2 PMSM vector control system block diagram[10]**

# Algorithm 2

### 3.5 Direct Torque Control

The working principle for the basic DTC is to select a voltage vector based on the error between requested and actual (sensed and estimated) values of torque and flux, rotor position estimation. DTC has the capability to work without any external measurement sensor for the rotors mechanical position. To satisfy the correct direction of rotation of a PMSM, the rotor position is required at the motor start up. DTC is simple because it does not require any kind of current regulators, rotating reference frame transformation or a PWM generator[12].

The advantages of the DTC is to eliminate the *dq*-axes current controllers, associated transformation networks, and the rotor position sensor. The disadvantages are low speed torque control difficulty, high torque and current ripple value, variable switching frequency, high noise level in low speed range.

Three signals affect the control action in a DTC system. They are namely .

1. Torque
2. The amplitude of the stator flux linkage
3. Angle of the resultant flux vector (angle between flux vector of stator and rotor)

The estimator obtains the torque and flux signal. Regulation of these two signals is done by the help of two hysteresis controllers. The rotor position estimator and the hysteresis controller give output signals to the switching table who in turn selects switching of the three inverter legs, and applies a set of voltage vectors across the motor terminals.

For counter-clockwise operation,

If the sensed torque is lesser than the required the voltage vector which keeps $\Psi_s$ rotation in the same direction as previous is chosen. The moment in which the measured torque is greater than the reference, the voltage vector which keeps $\Psi_s$ rotation in the opposite direction is aplied.

By selecting the voltage vector in this manner, the stator flux vector is rotated all the times It's rotational direction is obtained by the torque hysteresis controller output. If the estimated flux linkage is lesser than the required value then Φ=1. Same case applies to the torque.

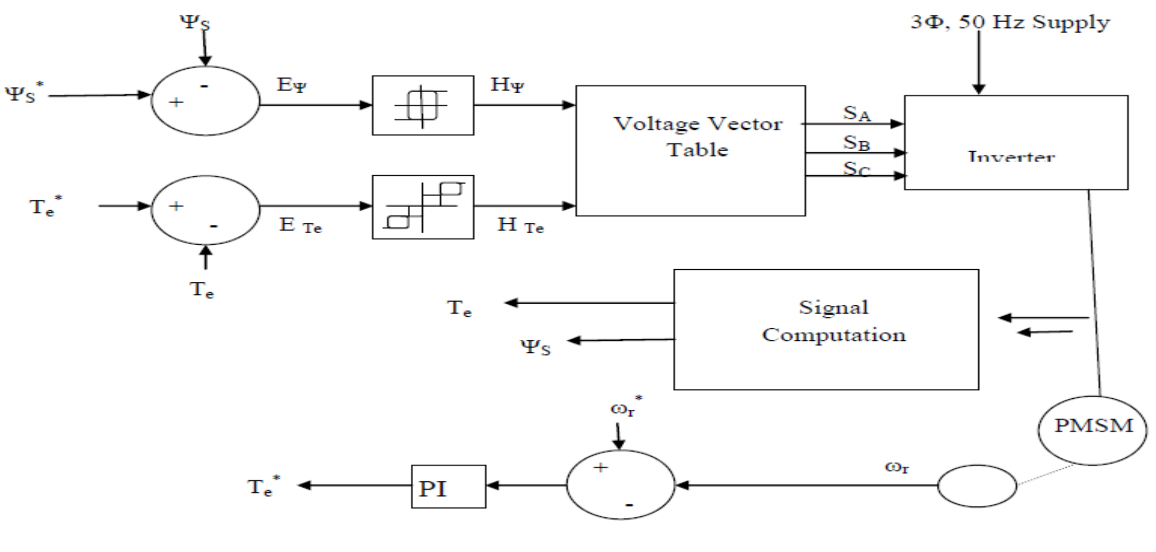


**Figure 3.3 Schematic of Direct Torque Control**.[12]

### 3.5.1 Current Transform

The measured motor currents are calculated with the Clarke transform from abc phase reference frame into the dq reference frame.

### 3.5.2 Voltage Transform

The voltage $u_{Set}$ is estimated from the inverters switching state and the DC-link voltage in the reference frame by the voltage equation.

$$u_{Set}(S_{abc}) = \sqrt{\frac{2}{3}}\frac{U_{dc}}{2}(S_a e^{0i} + S_b e^{2\pi i/3} + S_c e^{4\pi i/3}) - \sqrt{\frac{2}{3}}(u_a e^{0i} + u_b e^{2\pi i/3} + u_c e^{4\pi i/3}) \qquad (3.1)$$

where $S_{abc}$ is the state of the switches and $u_{abc}$ is the voltage loss in the switches.

### 3.5.3 Methods for Estimation of Stator Flux in DTC

Accurate flux estimation in DT controlled PMSM system is required to have proper drive operation, it's stability. Most of the flux estimation techniques known is based upon voltage modelling, current modeling, or combination of both of these. The estimation based upon current is generally applied at low frequency, and the knowledge of the stator current and rotor mechanical speed or position is required in this case.

By using rotor parameters for the estimation there is high introduction of error at higher speed of rotation due to the variations in rotor parameters. Hence this DTC control method the flux and torque are calculated by the help of voltage model described by (3.2)-(3.3). There is no need of a position sensor and the only stator resistance is used as amotor parameter.

$$\Psi_{s\alpha} = \int (V_{s\alpha} - R_s i_{s\alpha})dt \qquad (3.2)$$

$$\Psi_{s\beta} = \int \left(V_{s\beta} - R_s i_{s\beta}\right)dt \qquad (3.3)$$

### 3.5.4 Torque Calculation

The torque is calculated by the following equation.

$$T_e = \frac{3}{2} P \left( \psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha} \right) \tag{3.4}$$

### 3.5.5 Angle Calculation

By the help of flux linkage vector in the $\alpha\beta$ coordinates, location of the sector of the stator flux linkage vector is possible. The sign of the $\psi_\alpha$ finds us the quadrant of the stator flux linkage vector and the given equation gives us the exact angular position of flux vector[12].

$$\theta_s = \tan^{-1} {}^{\psi_\beta}/_{\psi_\alpha} \tag{3.5}$$

| Sector | $\Theta_1$ | $\Theta_2$ | $\Theta_3$ | $\Theta_4$ | $\Theta_5$ | $\Theta_6$ |
|---|---|---|---|---|---|---|
| **Angle** | [-π/2, -π/6) | [-π/6, π/6) | [π/6, π/2) | [π/2,5π/6) | [5π/6, 7π/6) | [7π/6, 3π/2) |

**Table 3.1 Relation in between flux linkage sector and its position[12]**

### 3.5.6 Torque and flux hysteresis comparator[12]

To find out the correct commands for control purpose a flux and a torque hysteresis comparators can be used. The comparators calculate the error between the required values and estimated values, and hence obtain if the flux and torque vectors should be

1. Increased - Output is 1
2. Decreased - Output is -1
3. Constant - Output is 0

The torque comparator works with three levels, but the flux comparator works with only two levels, as the stator flux musn't be kept constant while operating the permanent motor.

### 3.5.7 Space vector calculation

For state (++- / 110)

$V_{a0}=V_{dc,}$ , $V_{b0}=V_{dc,}$ $V_{a0}=0$

$$V_S = V_{a0} + V_{b0}e^{2\pi i/3} + V_{c0}e^{-2\pi i/3} \quad (3.6)$$

$$V_S = V_{dc}(\frac{1}{2} + \frac{j\sqrt{3}}{2})$$

$$V_S = V_{dc}\angle 60°$$

Similarly the switching vectors can be computed for the rest of the inverter switching state

.

| **Switching State [a b c]** | **Space Vector $V_s$** Rectangular form | Polar form(in degree) |
|---|---|---|
| $\mathbf{V_0}$ **[0 0 0]** | $V_{dc}(0+i0)$ | $0\angle 0$ |
| $\mathbf{V_1}$ **[1 0 0]** | $V_{dc}(1+i0)$ | $V_s\angle 0$ |
| $\mathbf{V_2}$ **[1 1 0]** | $V_{dc}(0.5+i3^{1/2}/2)$ | $V_s\angle 60$ |
| $\mathbf{V_3}$ **[0 1 0]** | $V_{dc}(-0.5+i3^{1/2}/2)$ | $V_s\angle 120$ |
| $\mathbf{V_4}$ **[0 1 1]** | $V_{dc}(-1+i0)$ | $V_s\angle 180$ |
| $\mathbf{V_5}$ **[0 0 1]** | $V_{dc}(-0.5-i3^{1/2}/2)$ | $V_s\angle 240$ |

**Table 3.2 Different switching states and corresponding space**

### 3.5.8 Look Up Table

The inputs table are given in terms of +1, 0,-1 depending on whether the torque and flux errors within or outside hysteresis bands and the sector in which the flux sector presents at that particular instant. The stator flux modulus and torque errors tend to stay within their hysteresis bands[12].

## LOOK-UP TABLE

| **Flux Error dψ** | **Torque Error dT** | **S1** | **S2** | **S3** | **S4** | **S5** | **S6** |
|---|---|---|---|---|---|---|---|
| | 1 | V2(110) | V3(010) | V4(011) | V5(001) | V6(100) | V1(100) |
| **1** | 0 | V0(000) | V7(111) | V0(000) | V7(111) | V0(000) | V7(111) |
| | -1 | V6(100) | V1(100) | V2(110) | V3(010) | V4(011) | V5(001) |
| | 1 | V3(010) | V4(011) | V5(001) | V6(100) | V1(100) | V2(110) |
| **0** | 0 | V7(111) | V0(000) | V7(111) | V0(000) | V7(111) | V0(000) |
| | -1 | V5(001) | V6(100) | V1(100) | V2(110) | V3(010) | V4(011) |

**Table 3.3 Look-Up Table**

### 3.5.9 Voltage Source Inverter

In DTC strategy an inverter is required for the conversion of the low voltage control signals to high voltage requires motor driving signals. The inverter is connected to the motor voltage terminals and whose control is achieved by three signals $S_{abc}$. Each signal controls high and low side power switches of the corresponding phase.

### 3.5.10 Controller

Proportional plus integral (PI) controllers are normally preferred, but the output characteristics of the PI controllers are changed by parameter variations, load disturbances and speed fluctuations. These problems are ignored by the FLC. But the performance of the fuzzy controller in comparison with to  PI controller is better only in case of  transient conditions. PI controller has the drawback that to assure it's proper performance, there is limits on the controller gains and the rate at which these would change have to carefully chosen. It has been seen that fuzzy controllers are robust to plant parameter changes than PI or PID controllers and have better noise rejection abilities[11].

The classical PI controller suffers from overshoot and undershoots of output, when any kind of nonlinearity is present in the system.

**3.5.10.1Fuzzy Logic Controller[11]**

The fuzzy logic can be considered as a theory which is combination of multi-valued logic, probability, and artificial intelligence which simulate the human approach for the solution of many problems by the use of an approximate reasoning.

A. Membership Functions

The FLC converts the crisp error and change in error into fuzzy variables and maps them to linguistic labels. Membership functions are linked with each label which comprises of 2 inputs and 1 output.

B. Knowledge Rule Base

The mapping of the inputs into the required output is derived by the help of a rule base.Each rule of the FLC has an IF part, known as antecedent, and a THEN part popularly the consequent.

C. Defuzzification

Normally the output is fuzzy in nature and hence is converted back into a crisp by the use of Defuzzification technique.

# Algorithm 3

### 3.6 Torque Control (SV-PWM)

The traditional DTC uses bang-bang control method to have speed control. But this is unable to meet the needs of both of torque and flux at the same instant, which causes huge variations of flux linkage and torque by the system and leads towards the pulse current and switching noise. [10].

$i_{sd}$ and $i_{sq}$, the part of $i_s$, in the d-q axis, is calculated by the phase current sampling datas $i_a$ and $i_b$. Then $\Psi_{sd}$, $\Psi_{sq}$ and $T_e$ are estimated by the help of $i_{sd}$ and $i_{sq}$. This uses 3-way closed-loop control of speed, flux linkage and torque. Takingspeed variation as $\Delta\omega_r$ as input, outer of loop PI controller output gives $T_e$. Then by taking torque error $\Delta T_e$ as input, torque loop PI controller is ouput which is in the form of $d\delta$ that is the correction value of $\delta$. This also represnts the angle between $\Psi_{PM}$ and $\Psi_s$. $u_{sd}$ and $u_{sq}$ is estimated from $d\delta$, $\Psi_{sd}$ and $\Psi_{sq}$. SVPWM control signals is obtained by inverse Park transformation of $u_{sd}$ and $u_{sq}$, and then driving the PMSM[13].

$$\Psi_{sd} = L_{sd} i_{sd} + \Psi_{PM}$$

$$\Psi_{sq} = L_{sq} i_{sq}$$

$$|\Psi_{sr}| = \sqrt{\Psi_{sd}{}^2 + \Psi_{sq}{}^2}$$

$$\delta = arctan \frac{\Psi_{sq}}{\Psi_{sd}}$$

Torque estimator can be expressed as:

$$T_e = \frac{3}{2}(\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd})$$

Where, dt is flux sampling interval, $\Psi_{sr}^*$ is known torque stator flux linkage.

$$d\Psi_{sd} = \Psi_{sr}^{*}\cos(\delta + d\delta) - |\Psi_{sr}|\cos\delta$$

$$d\Psi_{sq} = \Psi_{sr}^{*}\sin(\delta + d\delta) - |\Psi_{sr}|\sin\delta$$

To reduce the arithmetic, $d\Psi_{sd}$ and $d\Psi_{sq}$can be expressed as:

$$d\Psi_{sd} = \Psi_{sr}^{*}\left(\frac{\Psi_{sd}}{|\Psi_{sr}|}\cos d\delta - \frac{\Psi_{sq}}{|\Psi_{sr}|}\sin d\delta\right) - \Psi_{sd}$$

$$d\Psi_{sq} = \Psi_{sr}^{*}\left(\frac{\Psi_{sq}}{|\Psi_{sr}|}\cos d\delta + \frac{\Psi_{sd}}{|\Psi_{sr}|}\sin d\delta\right) - \Psi_{sq}$$

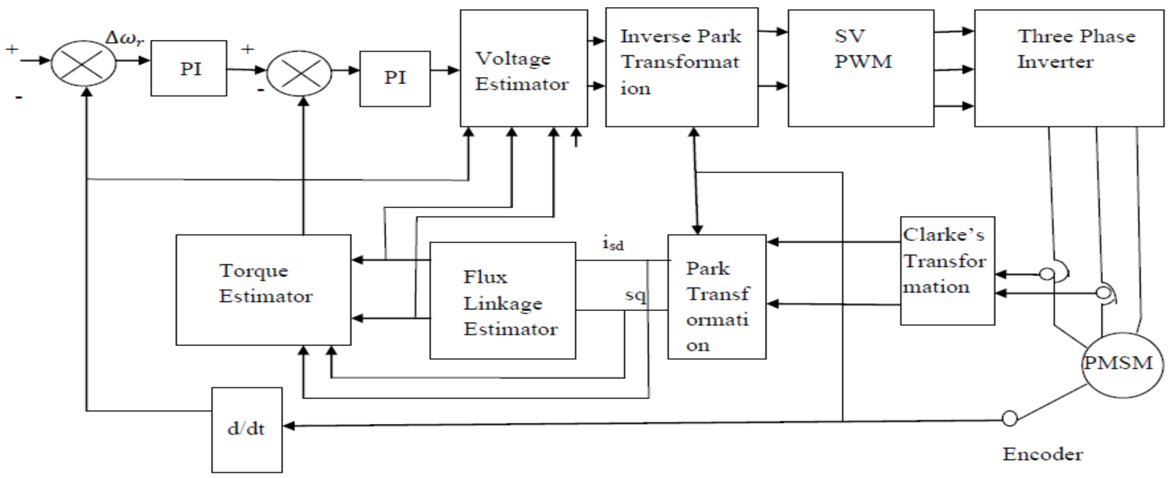


Figure 3.4 Block Diagram of Torque Control (SV-PWM) System[13]

### 3.6.1 Principle Of Space Vector PWM

To have the SVPWM, the voltage equations of the abc frame of reference is transformed into the stationary α-β reference frame. Six nonzero vectors ($V_1$ – $V_6$) shape the corner of a hexagonal feed power to the load or DC voltage is supplied to the load. The eight vectors are known as the basic space vectors.

The same transformation can be applied to get required output voltage for getting the reference voltage in d-q plane. The motive of SVPWM scheme is to approach the reference voltage vector using the given switching patterns[10].

# Chapter 4

# Simulations

MATLAB/ Simulink® 2010a 7.0 version software is used to perform the simulation during this work. Different models has been developed for different speed control scheme in accordance with the theory discussed in chapter 2 and 3. All the simulations are performed in discrete environment with sampling time in the order of microseconds. For first two of the given model ode45 is used for successful run of the simulation where as ode23 numerical algorithm is used for the last one. The machine parameters during simulation is specified in the Table 4.1 given below.

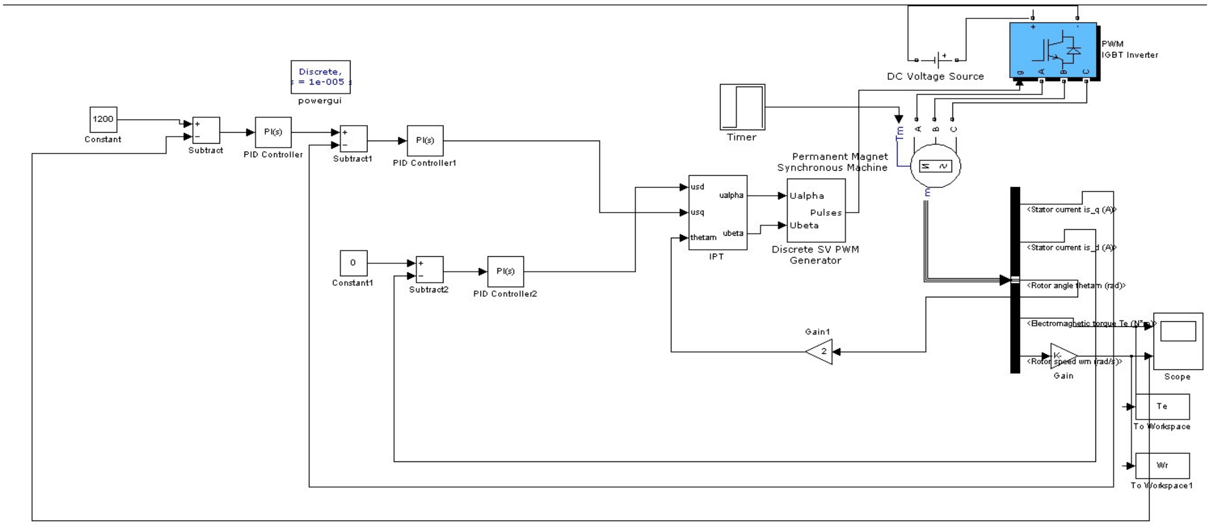


**Figure 4.1 PMSM FOC model Using MATLAB/Simulink®**

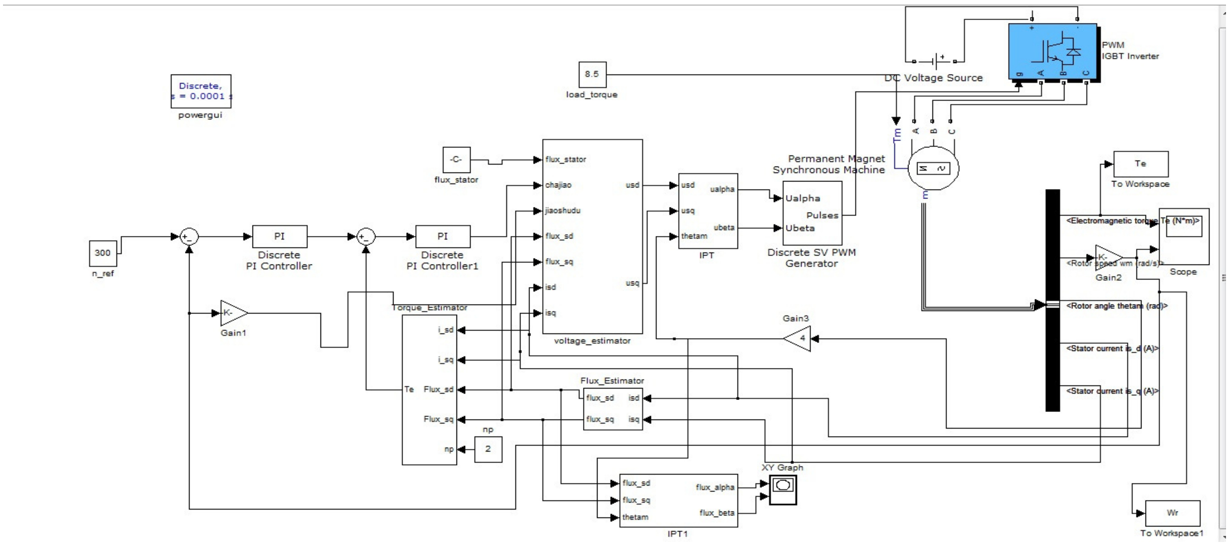

**Figure 4.3 Simulation Model Of PMSM DT-SVPWM System Using MATLAB/Simulink®**

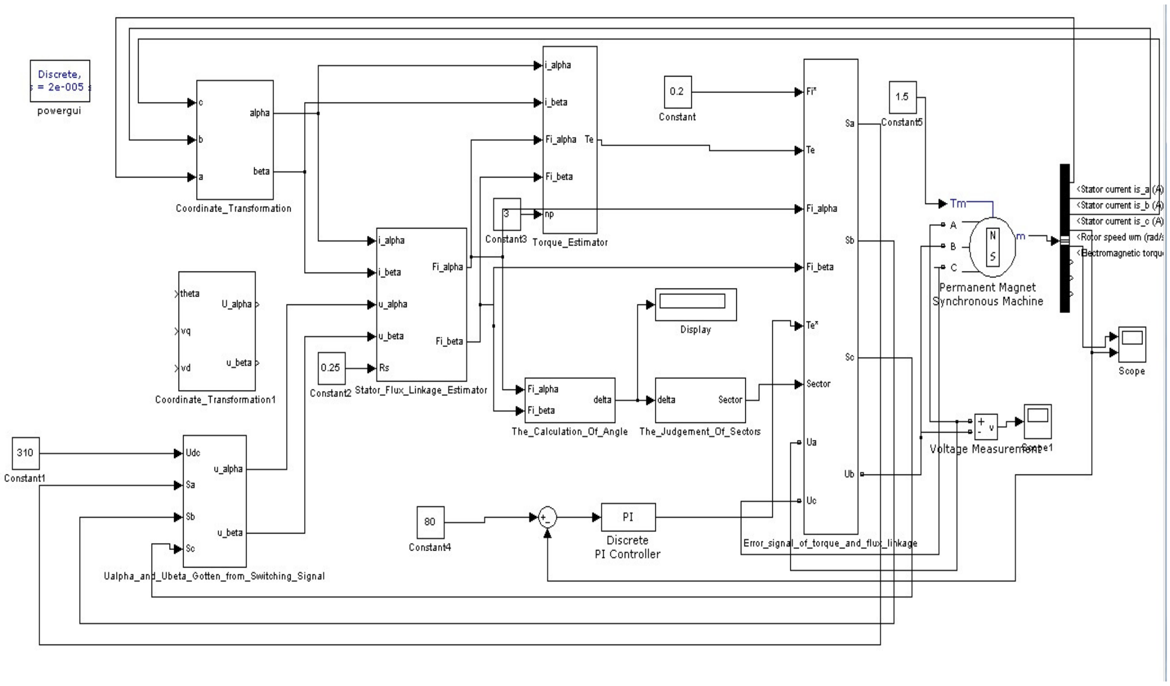


**Figure 4.2 Simulation Model Of PMSM DTC System Using MATLAB/Simulink®**

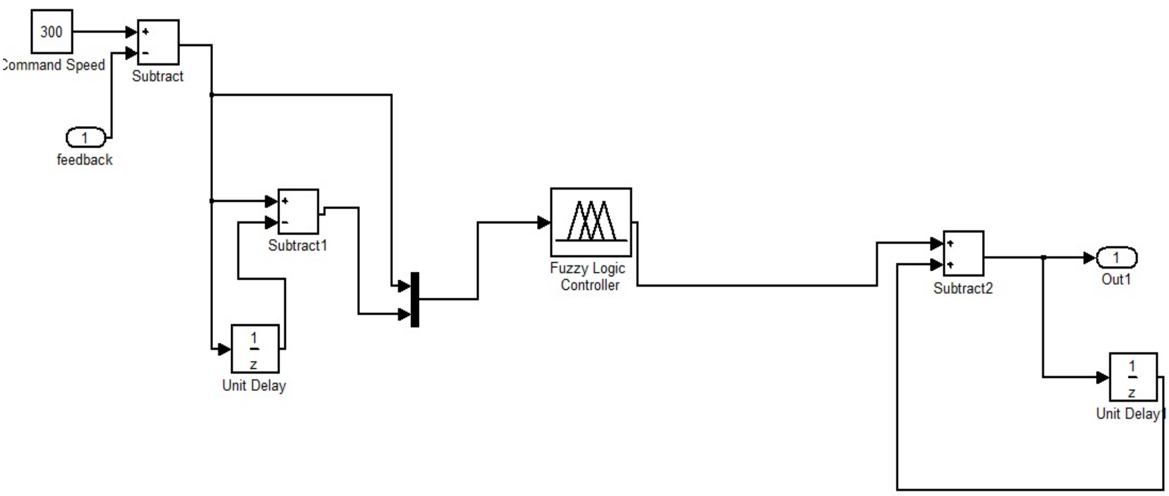


**Figure 4.4 The Fuzzy Logic Controller**

**Specifications**

| | | | |
|---|---|---|---|
| **1** | **$R_s$** | **Stator Resistance** | **0.96Ω** |
| **2** | $L_d$ | d-axis inductance | 5.25mH |
| **3** | $L_q$ | q-axis inductance | 5.25mH |
| **4** | $\Psi_f$ | Rotor flux linkage | 0.18Wb |
| **5** | J | Inertia | $.0008 kg.m^2$ |
| **6** | $n_p$ | Pair of poles | 2 |

**Table 4.1 Data of PMSM's Parameters**

# Chapter5

# Results and Discussions

### 5.1 Field Oriented Control

In Figure 5.1 load torque of 8.5N-m is applied at 0.5s of the simulation and removed in 1.5s. The electromagnetic torque varies in accordance with the load torque. Figure 5.2 shows that the reference speed is 1200 rpm and there is fluctuation in speed at instant of application or removal of torque though speed practically remains constant for variation in speed. This characteristic is obtained by having proportional gain 2 and integral gain 0.1 of the PI controller.

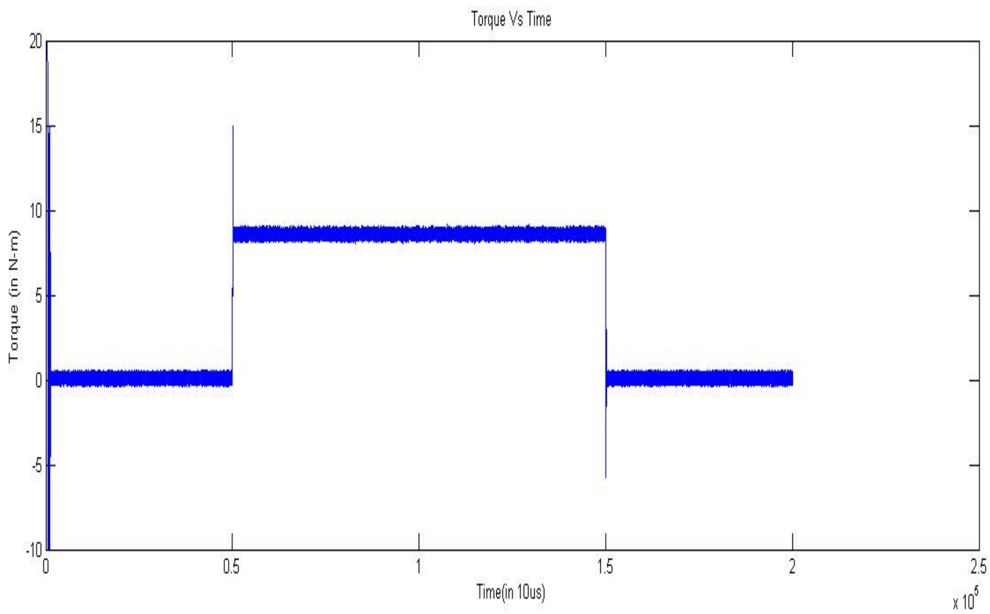


**Figure 5.1 Torque Vs Time Plot Under load condition FOC**

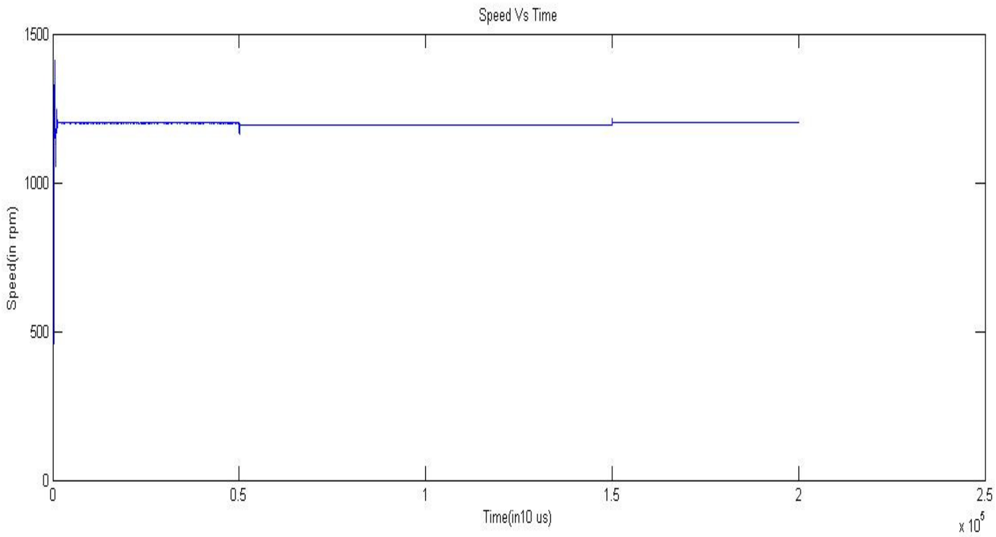


**Figure 5.2 Speed Vs Time Plot Under load condition FOC**

## 5.2 Direct Torque Control

### 5.2.1 No-load Condition

The Figure 5.3 shows the variation in orthogonal flux linkage values with respect to each other. The almost circular XY Plot gives the idea about constant magnitude of overall stator flux linkage which has to be the ideal case. Figure 5.4 represents the variation of three phase stator current in no-load condition.

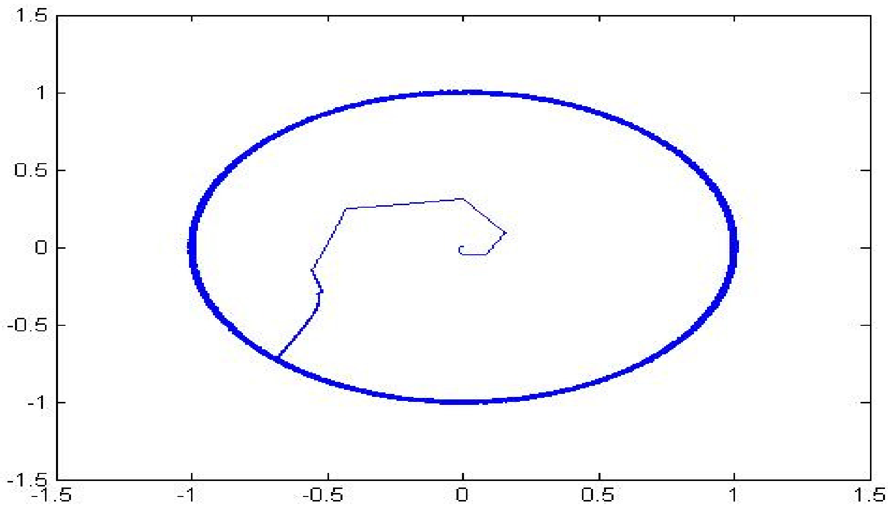


**Figure 5.3 Stator Flux Linkage XY Plot under noload codition DTC**

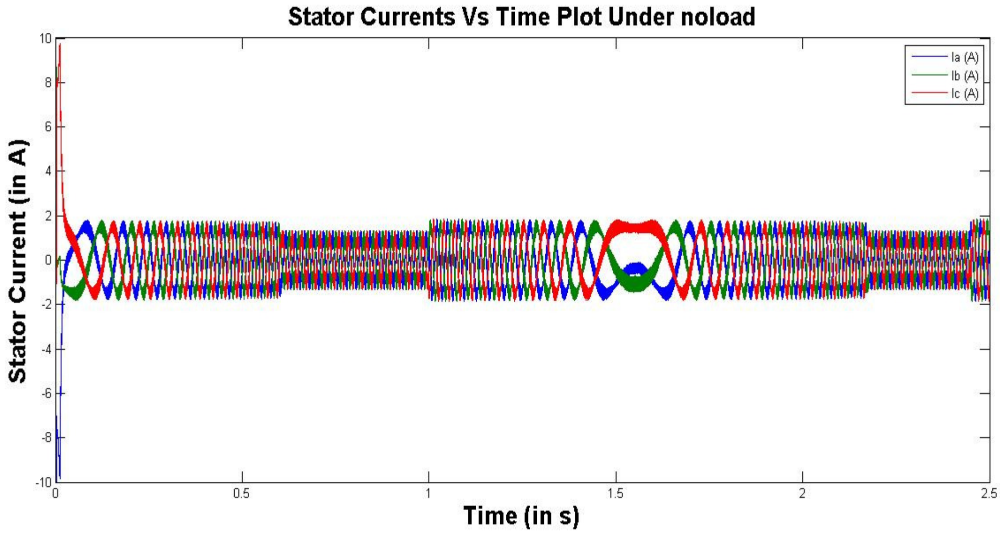


**Figure 5.4 Stator Currents Vs Time Plot Under noload condition DTC**

Under no-load the speed value is 1200 rpm. But it takes 0.6s time to reach the value from zero. At this time the torque is constant 20N-m. When the speed stops changing steady state torque value becomes zero. Then the system is driven in opposite direction for the same value of speed. Here Torque, Speed Plots are presented in Figure 5.5 and 5.6 respectively.

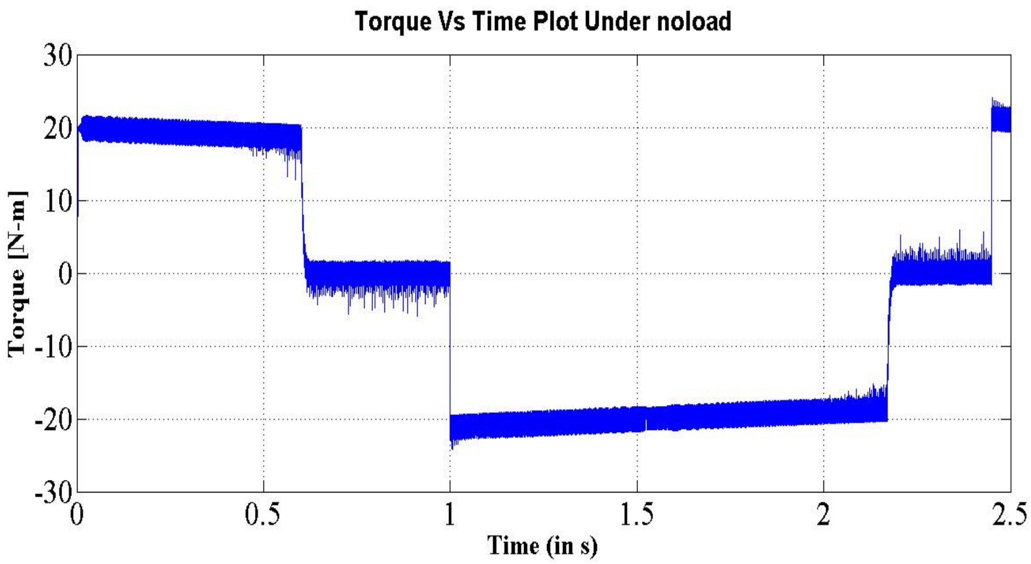


**Figure 5.5 Torque Vs Time Plot Under noload condition DTC**

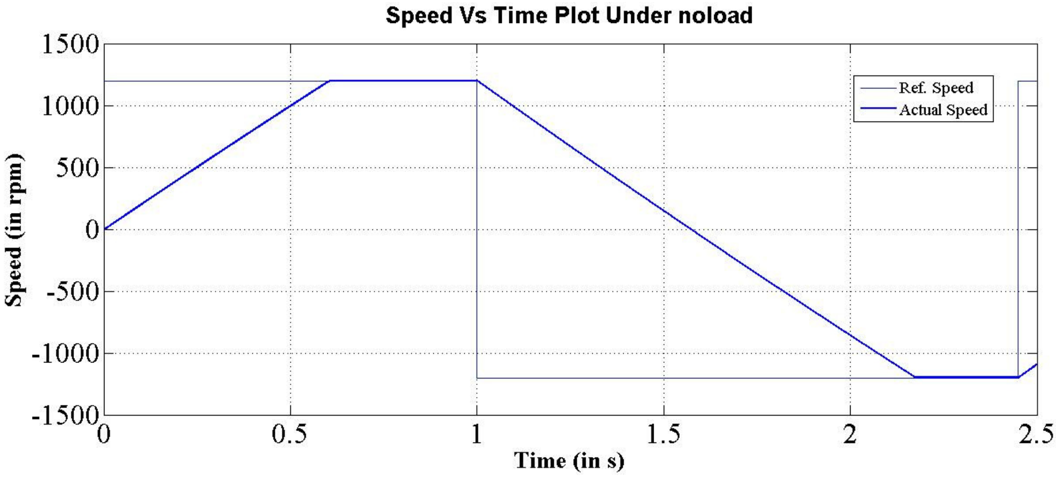


**Figure 5.6 Speed Vs Time Plot Under noload condition DTC**

### 5.2.2 Un load Condition

Figure 5.7 represents the variation of three phase stator current in under load condition. This systematic variation of gate pulses results in nearly sinusoidal variation of balanced 3-phase currents. Under loaded condition the reference speed value is same 1200rpm and it takes 0.6s to reach to this speed hence torque is first 20N-m and drops to zero at this instant of time. At t=0.7s a load torque of 5N-m is applied for which the torque value is changed is the plot and when the same is removed torque again becomes zero. Then the system is driven in opposite direction for the same value of speed. Here Torque, Speed Plots are presented in Figure 5.8 and 5.9. Considerable amount of ripples are present in torque and currents in both no-load and load cases.

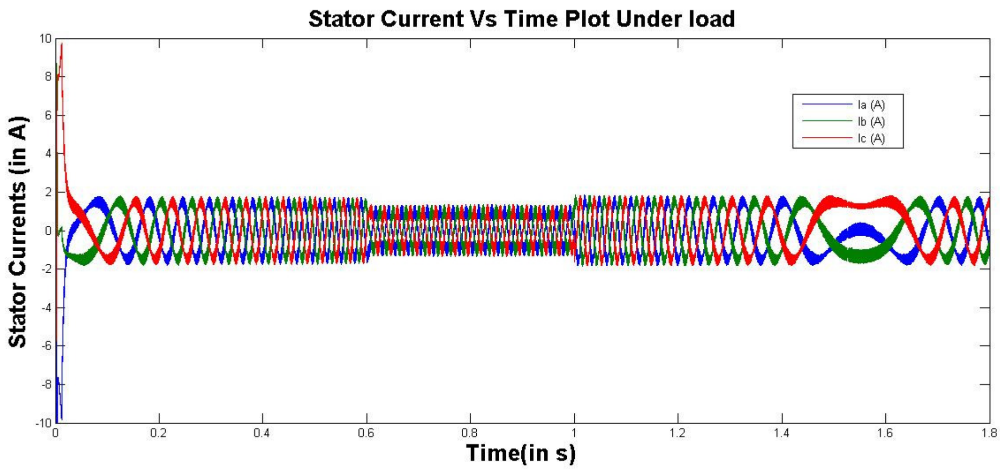


**Figure 5.7 Stator Currents Vs Time Plot Under load condition DTC**

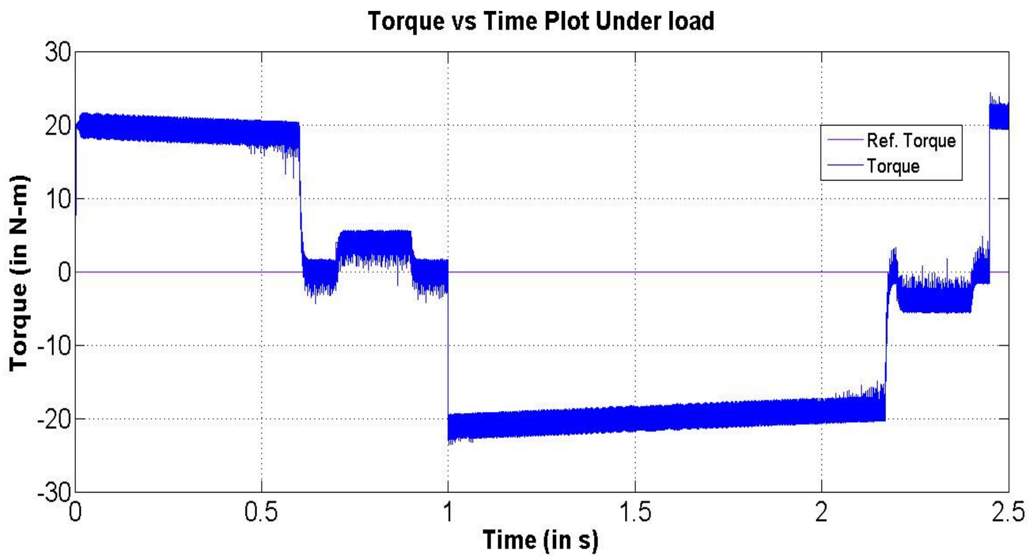


**Figure 5.8 Torque Vs Time Plot Under load condition DTC**

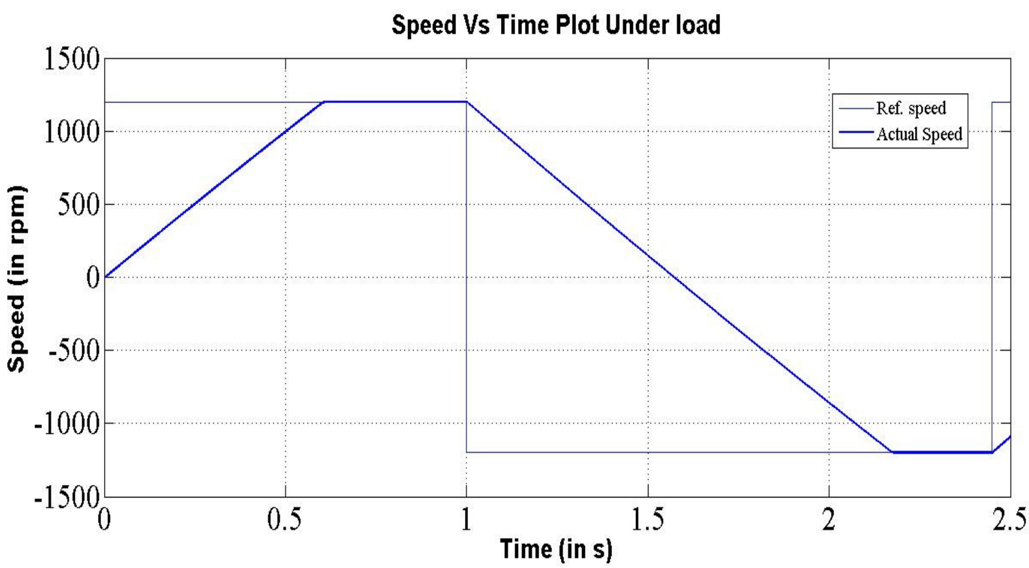


**Figure 5.9 Speed Vs Time Plot Under load condition DTC**

Figure 5.10 represents somewhat magnified view of the load torque application interval. The amount of ripple present is related to the band of hysteresis comparator which is $\pm 0.1$ in the present case. The smaller the value of the band the less is the fluctuation in the torque value.

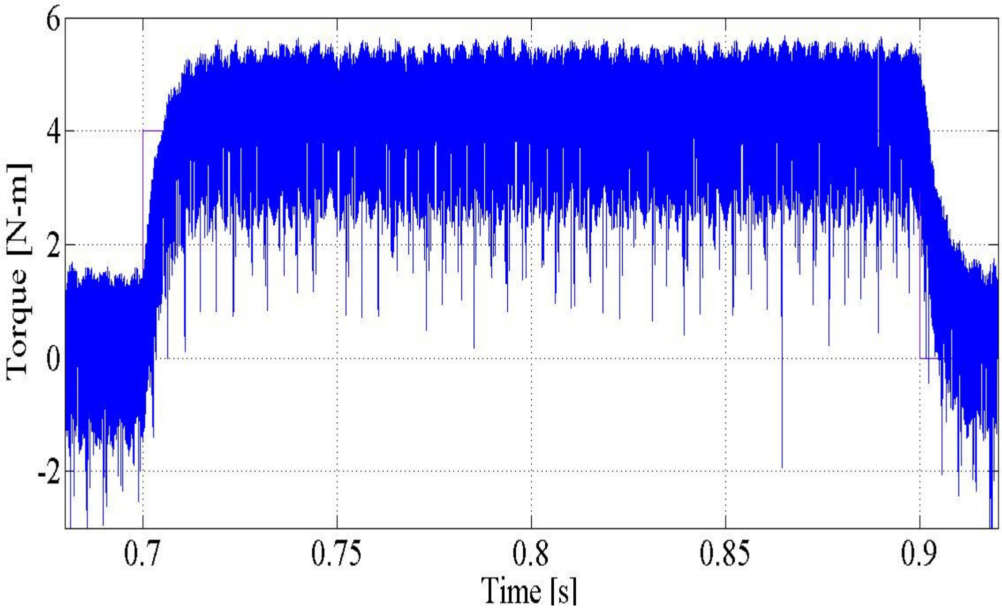


**Figure 5.10 Torque Vs Time under load condition DTC**

### 5.3 Direct Torque Space Vector Pulse Width Modulation Control

Figure 5.11 and 5.12 presents the performance characteristics of PMSM when a constant load torque of 8.5N-m and reference speed of 600rpm is given to the system. The system being stable achieves the required values with some steady state error.

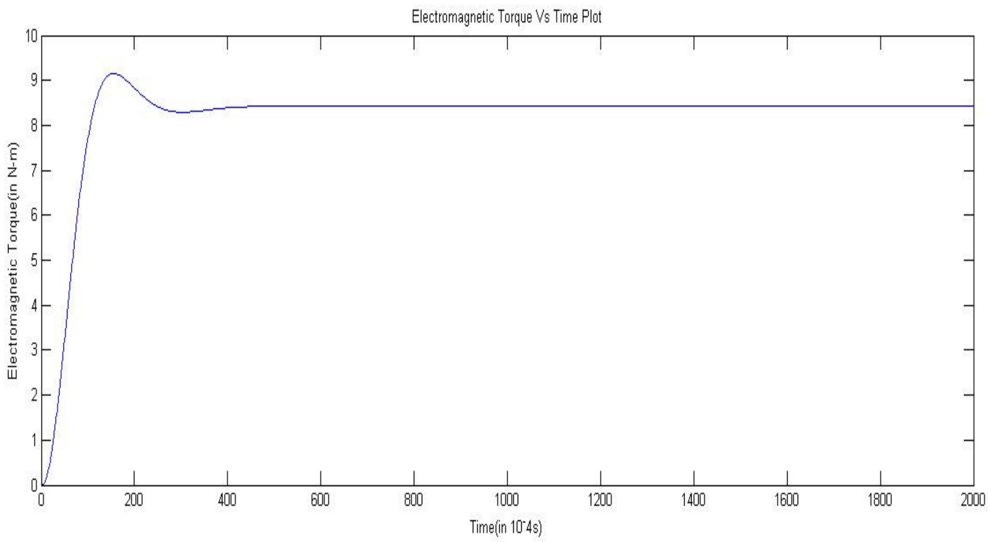


**Figure 5.11 Torque Vs Time DTSV-PWM**

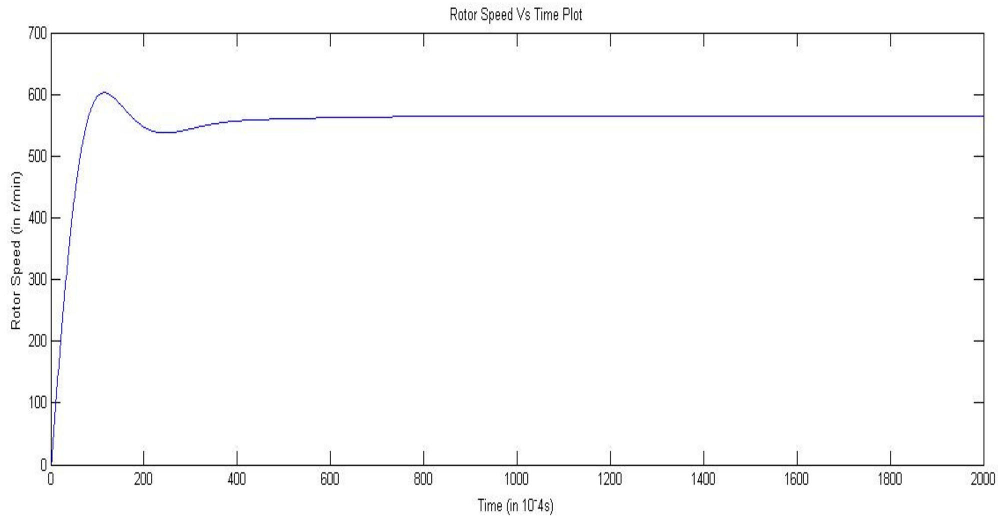


**Figure 5.12 Speed Vs Time DTSV-PWM**

Figure 5.13 again presents the dq-axis flux variation with respect to each other which is almost circular in shape.

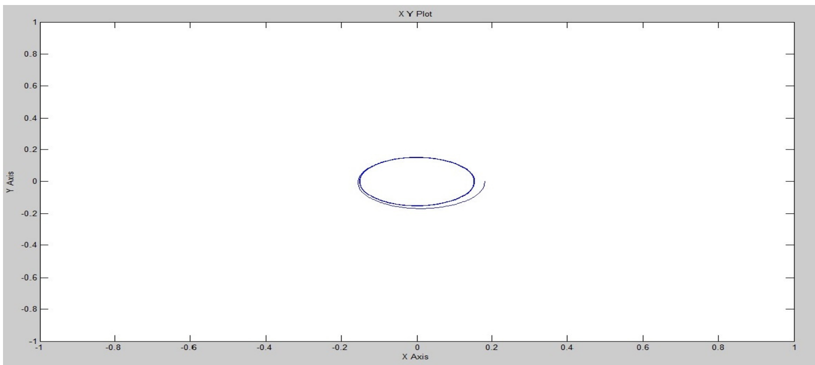


**Figure 5.13 Flux linkage response Curve (XY Plot) DTSV-PWM**

Figure 5.14 represents the variation of electromagnetic toque when a 8.5 N-m load torque is applied at t=0.5s and removed at t=1.5s. Figure 5.15 shows the variation of speed with the torque variation, the reference speed being 2700rpm.

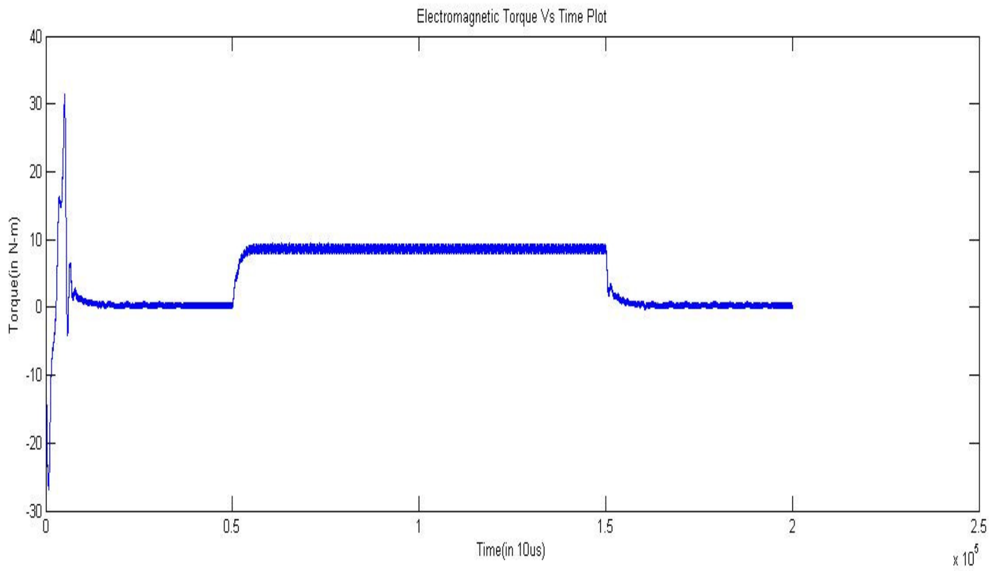


**Figure 5.14 Torque Vs Time DTSV-PWM under load**

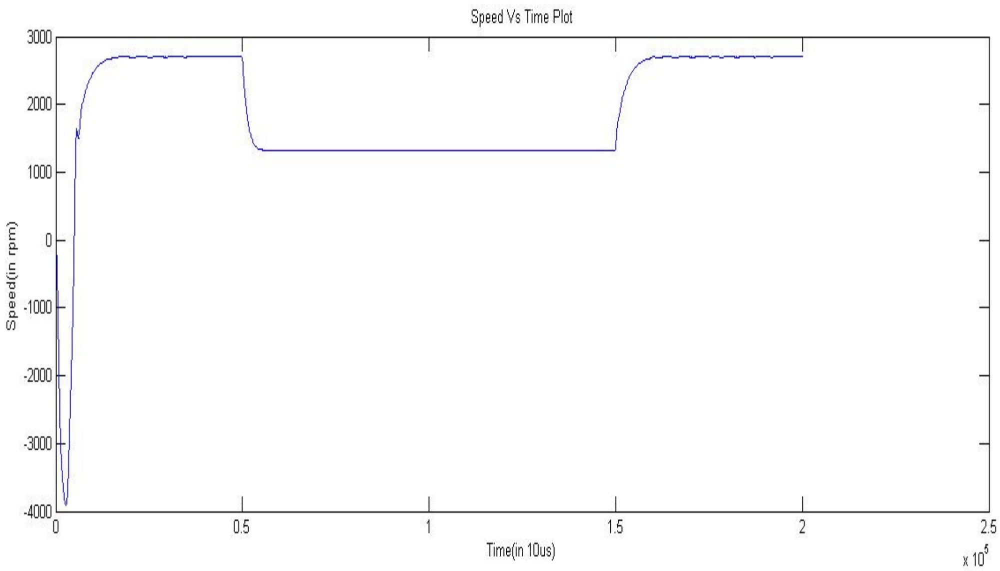


**Figure 5.15 Speed Vs Time DTSV-PWM under load**

# Chapter 6

# Conclusion

DTC is used for efficient control of the torque and flux without varing the motor parameters and load value. The flux and torque can be directly controlled by the inverter voltage vector in DTC. Two independent PI or fuzzy logic controllers can be used in order to satisfy the limitations on speed and torque. It can be concluded that DTC can be applied for the PMSM and is useful for a wide range of speed. Applications which require good dynamic performance demand DTC as it has a greaer advantage over other control methods because of its property of fast torque response. For the sake of increase of the performance indices, control period must be as short as possible. It is also practical for the sensitivity to keep the DC voltage in certain limiting value.

For the sake of improvement, a LP filter may be added to the simulation in order to eliminate the harmonics present along with the fundamental. Current Ripple Reduction with Harmonic back-EMF Compensation can be implemented to improve the performance characteristics.

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