SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR

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Submitted by
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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, “SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR”, in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology (Deemed to be University) is as authentic record of my own work carried under the supervision of Dr. Mukesh Singh. It refers others researcher’s work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

This thesis studies the field-oriented control (FOC) for speed control of Permanent Magnet based Synchronous Motor (PMSM) over the entire speed range, which is the vector control method. The main concept of the FOC strategy is to decouple the stator current into a torque developing part and a magnetic field developing part. This will simplify the control of PMSM, and the whole structure will look like a DC machine. This project aims to obtain smooth control of the entire speed range, faster acceleration, and faster deacceleration of the PMSM. To get vector control of PMSM, a MATLAB/SIMULATION model must be prepared. After getting the desired result from the model, a different Simulink model is to be designed, ready to implement on hardware.

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1. INTRODUCTION

With advancements in control techniques and the advancement of permanent magnet material, we could build a permanent magnet with a much higher flux density and perform way better. AC machine drives, particularly permanent magnet based synchronous motor and induction motor, have gain the popularity. No brushes mean it can improve motor performance lifetime significantly. PMSM drives have emerged as a bold option for a no. of applications in the current and future markets. Looking at these days, in applications like cars, a robotic systems, and a variety of other fields are examples. PMSM is preferred over other machines; many applications are now going towards permanent magnet-based synchronous machines because it has high torque density and high-power density. This high density is actually coming from the compact design. Because the permanent magnet technology is so advanced, we can now pack a lot of power and a lot of torque with a small footprint or a small volume which is much more advantageous. Field-oriented control can give an excellent performance for synchronous machines, especially PMSM. Implementing FOC on any digital signal processor hardware or micro-controller is one of the most challenging components of designing a vector control algorithm. In addition, a collaborative effort is necessary to construct the platform's required hardware modules.

This approach needs advanced coding skills, the practical-oriented experience of designing and implementing electronic circuits, a deep analytical knowledge of the proposed plan to be implemented, and an understanding of digital signal processor-based hardware or microcontrollers is required. Implementing a vector control algorithm may take a long time and effort, and the results may be unsatisfactory, discouraging further development in this area. By using Texas Instrument's launchpad along with the inverter booster pack, we can make a model in MATLAB/Simulink and deploy it to the Texas Instrument's launchpad. With this method, we can eliminate the coding efforts and minimize the required time for implementation. We will be using Texas Instrument's C2000 Microcontroller F28069M LaunchPad with TI's DRV8301 inverter booster pack. The F28069 Launchpad includes all of the functionality needed to control PMSM. It's also cost-effective, and low-power development hardware is required and it has a high performance.

The need for advanced programming skills is eliminated while using the F28069M launchpad. The F28069M launchpad may be coded using the package of Embedded Coder in the popularly used MATLAB environment, removing the requirement for sophisticated algorithms to be written in Embedded C code. While installing the Embedded coder package in MATLAB for the code generation requires essential supported software to be installed first. The supported software includes TI controlSUITE, TI Code Composer Studio, and TI C2000Ware. Where the TI Code Composer

Studio is required for deployment of code onto the F28069M launchpad, TI controlSUITE and TI C2000Ware are needed for code generation, provide design resources, documentation, application-specific libraries, etc., and thus minimize the system development time.

2. PERMANENT MAGNET SYNCHRONOUS MOTOR

Compared to back in the day, with the advancement of permanent magnet material, we could build a permanent magnet with a much higher flux density and perform way better. No brushes mean it can improve motor performance lifetime significantly. The rotor flux is provided by permanent magnets attached to the rotor, there is no need for a secondary source. PMSM is a result of this elimination [2]. As a result, PMSMs are commonly used in high-performance applications. Because the rotor of a PMSM has no current, rotor copper losses are minimal. Furthermore, there is no mention of the loss of stator current, which is a component of the system. The motor power factor is increased by the magnetizing current. Compared to other motors, these motors can be created with the same power but in a smaller size[3].

PMSM is preferred over other machines; many applications are now going towards permanent magnet-based synchronous machines because it has high torque density and high-power density. This high density is actually coming from the compact design. Because the permanent magnet technology is so advanced, we can now pack a lot of power and a lot of torque with a small footprint or a small volume which is much more advantageous along with the high rate of acceleration and deceleration. Looking at these days, in applications like cars, a robotic systems everything is trying to be compact, with very small designs. So compactness brings in another big factor along with efficiency. These PMSMs are very efficient compared to their counterparts, like induction machines. These PMSMs can be controlled electronically. It's called an electronically commutated. We can use inverters to control speed by controlling the current, and frequency, so having a variable frequency drive. PMSMs have the thermal advantage over the DC machine as the permanent magnets are installed on the rotor part and winding on the stator part, so heat dissipation is higher. In terms of cooling properties, we can cool the stator part much more efficiently compared to the rotor part. PMSMS are also known as outer runners.

2.1. Working of PMSM

The working principle is based on magnetic locking between the stator pole (formed due to the rotating magnetic field set up due to three-phase AC supply) and rotor poles (formed due to permanent magnets placed on the rotor). A three-phase supply is used to power the stator winding, which develops a rotating magnetic field in the air gap. This generates torque; the rotor field poles maintain a synchronous magnetic field, and the rotor rotates continuously.

Because of their high permeability, permanent magnets are made of Samarium-cobalt and medium, iron, and boron [4]. As a rotor, a permanent magnet is utilised to develop the magnetic field. Since no dc supply is actually needed to excite the rotor, permanent magnets are used instead of wound fields. It can be enhanced and made more reliable.

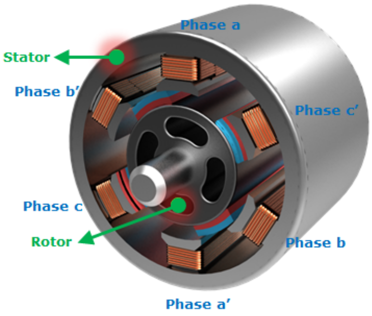


Figure 1: Three-Phase PMSM.[1]

2.2. Types of PMSM

2.2.1. PMSM classification based on field flux direction

I. Axial Field: - The direction of the stator flux vector is parallel to the shaft of the motor. Because of its high rate of acceleration and higher power density, axial field PMSM is now used in a variety of applications.

II. Radial Field: - In this type of PMSM, the direction of the stator flux vector is aligned with the radius of the motor. The most prevalent type is radial field PMSM.[5].

2.2.2. Classification of PMSM based on the placing of permanent magnets

A. Surface-mounted PMSM :-In this type of PMSM, the outer peripheral surface of the rotor is used to install the permanent magnets. The benefit of this kind of construction is that it provides the highest flux density in air gap; however, it has the disadvantage of reducing integrity of the structure. Further surface-mounted PMSM is classified into two types,

   I. Surface mount inset permanent magnet.[6]
   II. Surface mount permanent magnet.[6]

(a) Surface mount inset permanent magnet

(b) Surface mount permanent magnet

Figure 2: Surface-mounted PMSM

B. Interior magnet PMSM :- Permanent magnets are embedded within the rotor laminations of this type. This arrangement is more difficult to create than a surface mounts or inset permanent magnet rotor. Further interior buried PMSM is classified into two types are as follows,
    I. Interior magnet PMSM having a circular orientation [7]
    II. Interior magnet PMSM [7]

(a) Interior permanent magnet with circumferential orientation

(b) Interior permanent magnet

Figure 3: Interior buried PMSM

2.3. PMSM Modeling

For proper motor MATLAB/Simulation and design, an equivalent circuit is required. The model is obtained and resulting from the motor's d-q modelling, which use the stator's voltage derivations [8] [9].

2.3.1. *PMSM Equivalent Circuit*

The equivalent circuit of PMSM without dampper winding[10] is shown in the following Fig.4,

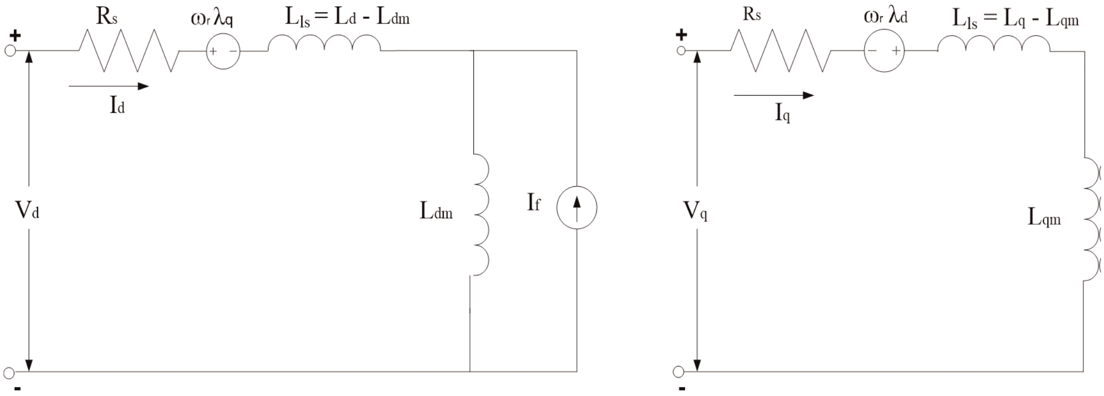


Figure 4: Equivalent circuit diagram of PMSM

Voltage equation is,

$$V_d = R_s i_d + \rho\lambda_d - \omega_r\lambda_q \tag{1}$$

$$V_q = R_s i_q + \rho\lambda_d + \omega_r\lambda_d \tag{2}$$

Equations of flux linkage,

$$\lambda_q = \lambda_f + L_q i_q \tag{3}$$

$$\lambda_d = L_q i_q \tag{4}$$

By putting values of λ_d and λ_q into Eq. (1) and Eq. (2)

$$V_q = R_s i_q + \omega_r(L_d i_d + \lambda_f) + \rho L_d i_d \tag{5}$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho(L_d i_d + \lambda_f) \tag{6}$$

By substituting Eq.(6) and Eq.(5) in matrix the form,

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \begin{pmatrix} -\omega_r L_q & R_s + \rho L_d \\ R_s + \rho L_q & \omega_r L_d \end{pmatrix} \begin{pmatrix} i_d \\ i_q \end{pmatrix} + \begin{pmatrix} \rho\lambda_f \\ \omega_r\lambda_f \end{pmatrix} \tag{7}$$

The developed motor torque is given by,

$$T_e = \frac{3p}{2}(\lambda_d i_q - \lambda_q i_d) \tag{8}$$

The mechanical torque equation is,

$$T_e = J\frac{\mathrm{d}\omega_r}{\mathrm{d}t} + B\omega_m + T_l \tag{9}$$

Computing for the rotor speed (mechanical) equation from Eq.(9),

$$\omega_r = \int \left(\frac{T_e - B\omega_m - T_L}{J}\right) dt \tag{10}$$

and

$$\omega_m = (\frac{2}{P}) * \omega_r \tag{11}$$

Where,

ω_r is rotor speed in electrical.

ω_m is rotor speed in mechanical.

The equation below shows conversions of the phase voltages variable from V_{abc} to V_{dq0} in the axis frame of rotor reference ,

$$\begin{bmatrix} V_q \\ V_p \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\Theta_r & cos(\Theta_r - 120) & cos(\Theta_r + 120) \\ sin\Theta_r & sin(\Theta_r - 120) & sin(\Theta_r + 120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{12}$$

Transform V_{dq0} to V_{abc}

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\Theta_r & sin\Theta_r & 1 \\ cos(\Theta_r - 120) & sin(\Theta_r - 120) & 1 \\ cos(\Theta_r + 120) & sin(\Theta_r + 120) & 1 \end{bmatrix} \begin{bmatrix} V_q \\ V_d \\ V_0 \end{bmatrix} \tag{13}$$

3. PMSM DRIVE SYSTEM

The drive system of PMSM is made up of the central control unit known as the controller and other units such as the inverter, Permanent magnet synchronous motor, and the sensor for rotor position. The interconnection of the PMSM drive system components are shown in the following Fig. 5,

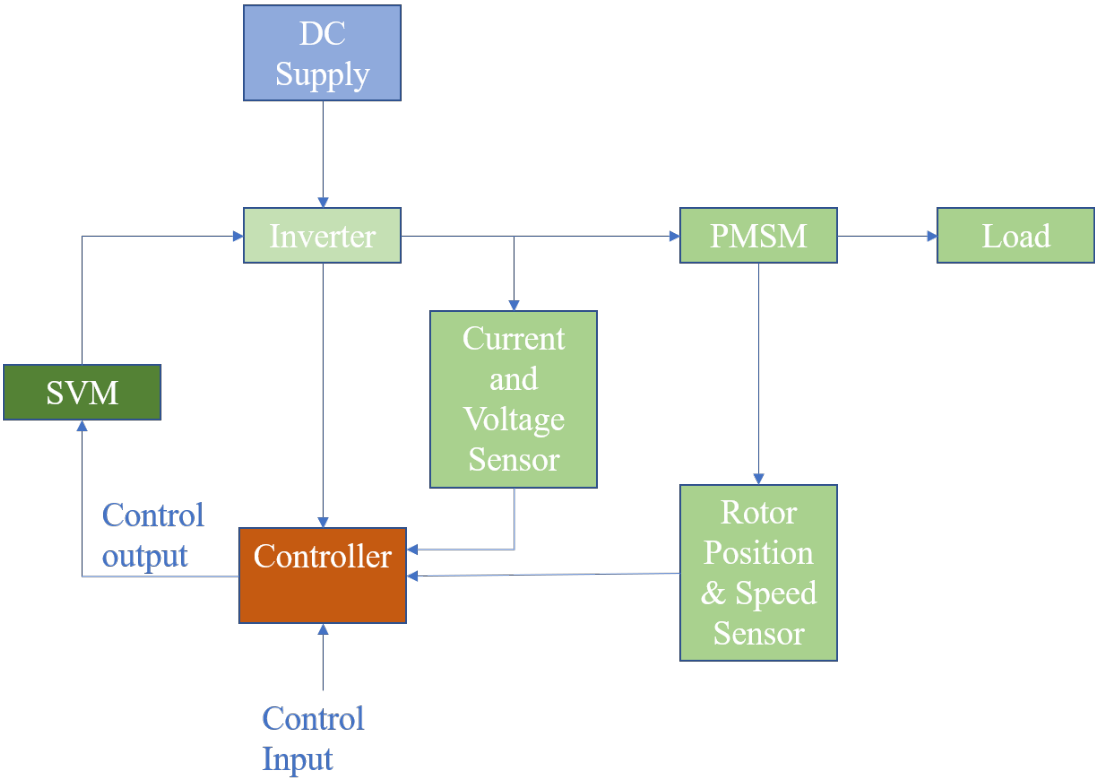


Figure 5: PMSM Drive System.

3.1. Controller

A controller is a device that helps to minimize the difference between its desired value and a system's real value. Controllers are often used in all sophisticated control systems, an essential aspect of control engineering [11]. It is crucial to understand how controllers are used. The controllers perform a number of functions, are given as follows,

i. The controller suppress unwanted offsets produced by the system.
ii. Controller improve steady-state authenticity by reducing error in steady-state.
iii. The stability is also improved as a result of improved steady-state authenticity.

iv. A controller is capable of controlling the maximum overshoot hit by the system.

v. A controller can also decrease the system's response time, which means the system responds quickly as soon as possible.

The need for a controller is discussed in the following points,

i. Today's electric power trains use BLDC or PMSM motors, which require a motor controller to perform effectively.

ii. The motor controller ensures balance and proper flow of energy within the motor.

iii. The motor controller can also reverse the energy from the motor back to batteries, which helps the electric vehicle brake more effectively than a Simple mechanical brake system, which also increases the range of the vehicle [12].

iv. Most motor controllers used in India are imported from China or other countries. To limit or reduce the import of the controllers, we have to start manufacturing with the help of local suppliers for the components as much as possible.

3.2. Control techniques of PMSM

In control systems, a wide range of control approaches are used. The ideal control strategy is determined mainly by the task assigned to the drive. The primary idea behind these methods is to regulate the magnitudes and angles of the space vectors individually or simultaneously. In the literature, many solutions on the basis of control techniques and both motor designs are offered [13] [14] . The classification of control techniques are shown in the following Fig.6,

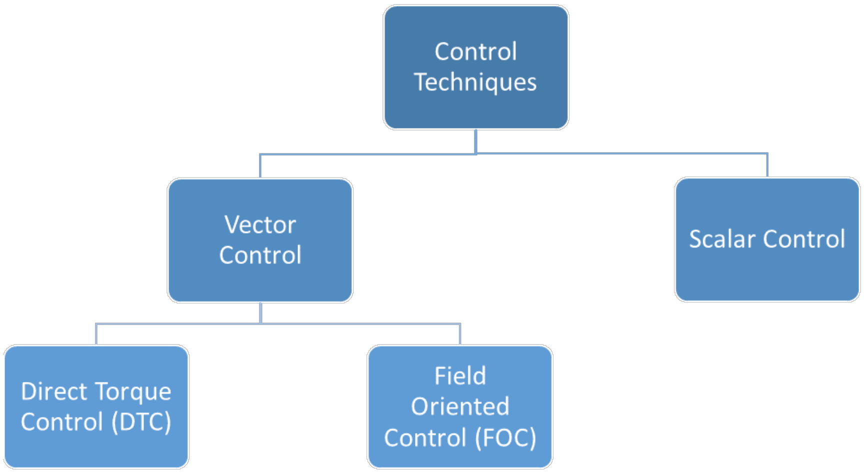


Figure 6: Control Techniques.

3.2.1. Scalar Control

The most common control strategy for AC motors is open loop scalar control, which controls AC machines for applications of variable speed [15]. Scalar control, now employed in applications that do not require angular speed. Because it assures reliability at the price of effective performance, this control strategy is suited for a variety of drives. The primary terminology is to vary voltage frequency of the supply without considering the rotor position (ω).

As the frequency changes in a constant ratio to the amplitude of the voltage supplied changes. The magnetic flux is moderate, and the motor is not overexcited or underexcited. As the application does not require any kind of information regarding the angular speed, the basic control technique can run in sensorless mode. On the other hand, the speed sensitivity depends on external load torque, especially in case of PMSM, and the poorer dynamic performances are important disadvantages.

3.2.2. Vector Control

This concept of control for PMSM, enables unique closed-loop regulation of both torque and flux, resulting in a control strategy similar to that of a DC machines [16] [17]. Electromagnetic torque is represented in d-q components of currents as:

$$T_e = \frac{3p}{2}\left[\varphi_{PM} i_q + i_q i_d (L_d - L_q)\right] \tag{14}$$

where L_q and L_d are the synchronous inductances on the q-axis ,and d-axis respectively. Each term in the above equation has a particular meaning. The first term ($\varphi_{PM} i_q$) is unaffected by i_d and i_q the current component of the stator is directly proportional.

The second term ($i_d i_q (L_d - L_q)$), on the other hand, is proportional to the product of i_q and i_d as well as the difference in inductances i.e ($L_d - L_q$). As indicated in equation (14) above, the torque dependent on the structure of rotor, synchronous inductance (L_q) & (L_d), and permanent magnet installed on rotor.

PMSM's with non-salient rotor contains surface mount permanent magnet, and the term reluctance vanishes when $L_d = L_q$. If permanent magnet placed on interior and motor's rotor saliency generates a difference between L_d and L_q, the reluctance component dominates the electromagnetic torque.

Vector control is mainly classified in to two types are as follows,

I. Direct torque control (DTC):- Best of the excellent performance control systems for an AC machine is the DTC [18]. DTC is an advance drive control concept for AC, in which switching of inverter immediately regulates variable of motor i.e torque and flux. Torque can be regulated by adjusting the linkage of stator flux vector amplitude constant and increasing the linkage of stator flux vector rotating speed as quickly as possible. By selecting the appropriate stator voltage, rotating speed and the amplitude of the stator flux vector may be regulated.

II. Field oriented control (FOC) of PMSM:- FOC is a method for controlling flux and torque independently by converting quantities of the stator current in frame of stationary reference to flux and torque producing current quantities in a frame of rotating reference, similar to a dc machine [19]. It advances both transient and steady-state responses of PMSM [2].

4. CONTROL OF PMSM BY FIELD-ORIENTED CONTROL

We can use different strategies to control a permanent magnet synchronous machine; one of the primary methods is FOC. We can use sensor on sensorless methods for controlling, but FOC can give an excellent performance regardless of the approach. FOC is also known as vector control. FOC has a certain complexity for a synchronous machine, especially for a permanent magnet synchronous machine. Still, certain advantages include speed control over the whole speed range and optimal torque generation.

The vector control algorithm works on the principle of decomposing a stator current into two parts, i.e., a part that is developing a magnetic field in the air gap and another is torque-developing. Following decomposition, these two components are controllable independently. Building such a the controller for a motor is nearly identical to that of a DC motor, simplifying control of a PMSM.

A permanent magnet rotor has a rotor flux vector which is established by the permanent magnet. As the winding is placed on the stator part, depending on the pattern of applying voltages and currents stator can establish a flux vector essentially another within the air gap. And we can actually orient the stator flux vector however, we want to based on the angle of the current. Three-phase power is provided to the stator winding (120 degrees out of phase) with this supply frequency, and a rotating flux vector is established in the air gap. If we hold the angle of the stator current at particular degrees, we can align the stator flux vectors at any specific angle to the rotor flux vector.

The force attempting to repel or attract both flux vector is greatest when they are 90° out of phase from each other. To place the stator flux vectors to be 90° out of phase from the permanent magnet flux vectors, we need to know the information about the machine state for placing the stator flux vector. Machine State means we need to know precisely where the permanent magnet flux vector is oriented or how it is placed because when the machine is rotating, this could be at any arbitrary position. Unless we know the position of the rotor flux vector, we cannot optimally place the stator flux vector. A position sensor is used to obtain information about the rotor flux vector position. At an instant where both flux vectors are 90° appart from each other, the following is the torque equation of a PMSM.

$$T_e = \frac{3p}{2}\left[\varphi_{PM} i_q\right] \tag{15}$$

where, φ_{PM} - flux developed by permanent magnet installed on rotor

p - number of pole pairs

i_q - amplitude of current in q-axis

When magnetic fields are perpendicular, torque is proportional to ‘ i_q’, as shown in previous equation. The controller must control the phase stator current magnitude as well as the phase/angle, as a DC motor controller, this is not an easy duty. Because all controllable quantities in a steady-state are DC values, and a mechanical commutator controls the current phase per angle, DC motor control is simple. In the cascade structure, we employ Pl controllers for magnitude control.

Carrying out the FOC algorithm requires both hardware and software parts. The hardware part involves the PMSM, inverter, a position measurement sensor, and the current sensors. The software part involves the decomposition of stator current. For the purpose of decomposition, it requires rotors location and transformation blocks for transforming the quantity of one reference frame to the other, i.e., from stationary to rotating or vice versa.

$$Electrical\ rotor\ position = \frac{Mechanical\ rotor\ position}{No.\ of\ pole\ pairs\ (p)} \tag{16}$$

Following a control technique, we must generate 3-phase AC voltages on motor terminals, so inverse Park/Clarke transformations should transform DC values of the required/generated voltage.

The essential operation of FOC is shown in the following block diagram, Fig.7

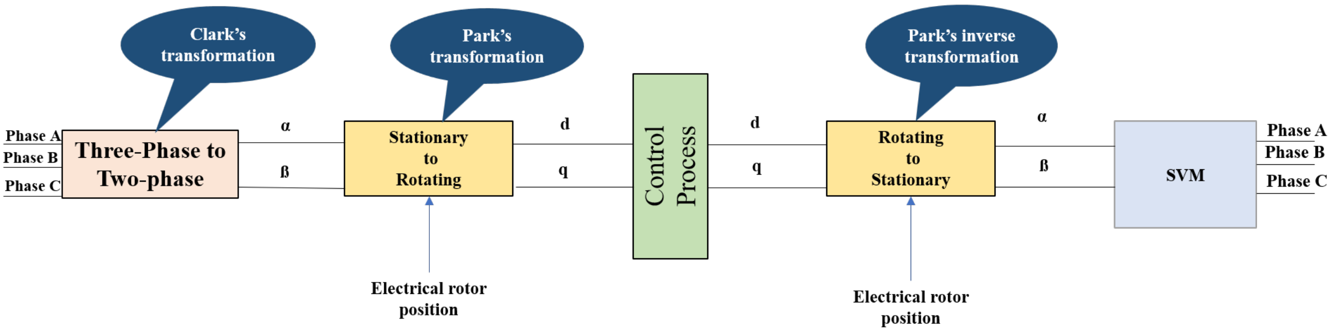


Figure 7: Block diagram of Basic Principle of FOC.

The above block diagram of FOC is explained in the following steps:

Step 1:- Determine the phase currents of the motor.

Step 2:- Using the Clarke transformation, convert them to a two-phase quantity (a, b).

Step 3:- Determine the rotor location (angle).

Step 4:- Using the Park transformation gives d, q co-ordinate from stator currents.

Step 5:- The controllers individually regulate the stator current’s flux (i_d) and torque (i_q) producing components.

Step 6:- Using the Park’s inverse transformation, output voltage of stator space vector is transformed back in d, q quantities into the two-phase quantity.

Step 7:- : Three-phase voltage output is developed via space vector modulation.

4.1. Speed Control of PMSM

The PMSM speed control is carried out by using PI controller in the field oriented control technique and system block diagram is shown below,

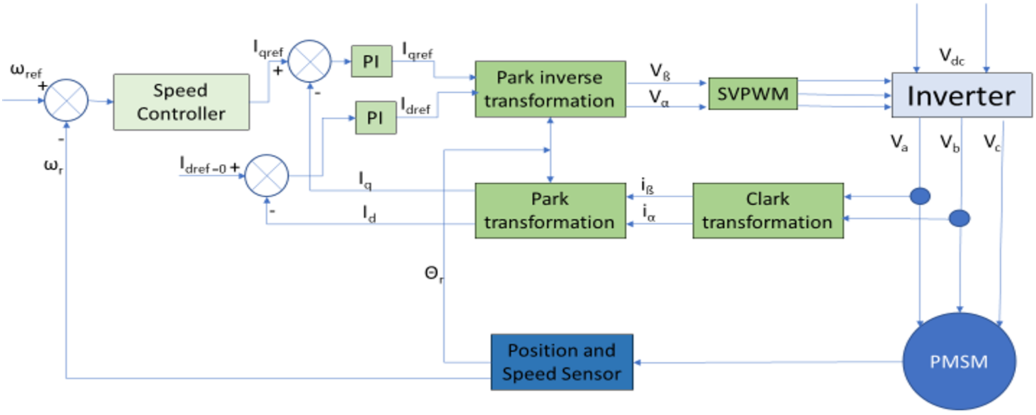


Figure 8: FOC Block diagram for PMSM

The stator currents i_d and i_q are compared with the reference value i_{qref} & $i_{dref} = 0$ (if no field weakening exists, set to zero to produce maximum torque.) and corrected using PI current controllers. The current controller's outputs are subjected to the inverse Park's transformation, and the SVPWM approach is used to impress a new stator voltage. An outer loop drives the reference current i_{qref} to control motor's speed in mechanical. PI controller calculates i_{qref}, by measuring the set speed to rotor's observed speed. To put it another way, the speed controller produces a reference torque corresponding to i_{qref}. The reference mechanical speed is represented by letter ' ω_{ref} '. Current sensors can obtain data of phase current, and a position sensor can obtain information about the rotor position.

4.1.1. Space Vector Pulse Width Modulation Principle

When compared to sinusoidal pulse width modulation, SVPWM is a advanced strategy for creating a basic sinusoidal waveform that offers a high voltage while reducing overall harmonic disturbance to the motor [20][21]. The space vectors strategy is often referred to as SVM (space vector modulation). SVM gives an excellent outcome for FOC. The switching sector is depicted in the Fig.9, and the inverter's switching vectors is depicted in the Fig.10.

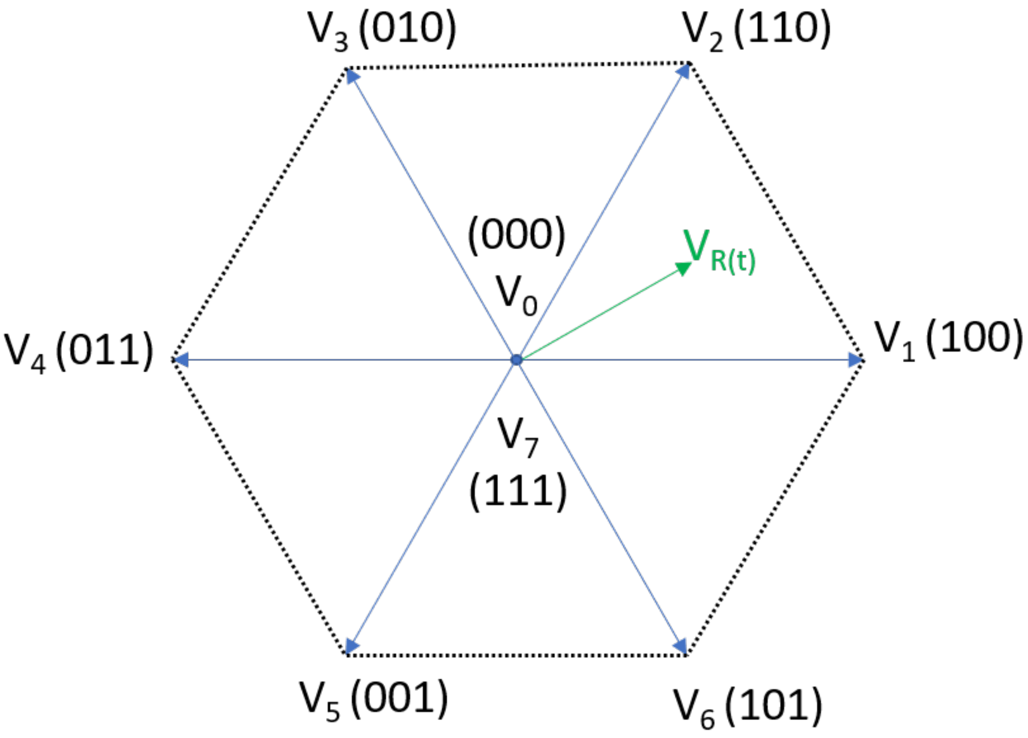
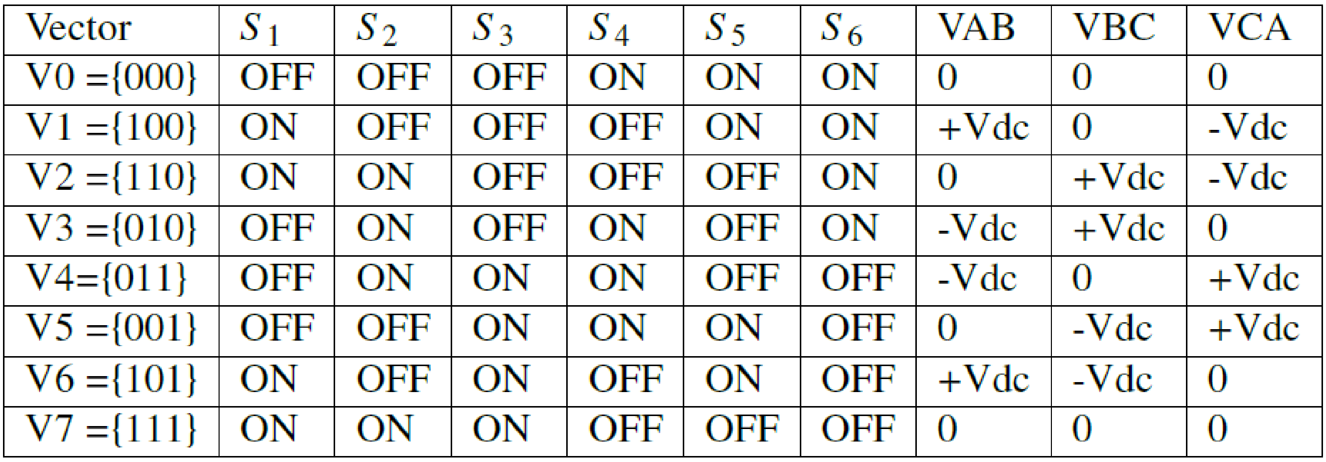


Figure 9: Switching vectors.



Vector	S_1	S_2	S_3	S_4	S_5	S_6	VAB	VBC	VCA
V0 ={000}	OFF	OFF	OFF	ON	ON	ON	0	0	0
V1 ={100}	ON	OFF	OFF	OFF	ON	ON	+Vdc	0	-Vdc
V2 ={110}	ON	ON	OFF	OFF	OFF	ON	0	+Vdc	-Vdc
V3 ={010}	OFF	ON	OFF	ON	OFF	ON	-Vdc	+Vdc	0
V4={011}	OFF	ON	ON	ON	OFF	OFF	-Vdc	0	+Vdc
V5 ={001}	OFF	OFF	ON	ON	ON	OFF	0	-Vdc	+Vdc
V6 ={101}	ON	OFF	ON	OFF	ON	OFF	+Vdc	-Vdc	0
V7 ={111}	ON	ON	ON	OFF	OFF	OFF	0	0	0

Figure 10: Inverter’s switching vectors

The concept of space vectors has come from the rotating MMF in machines. The resultant MMF for a three-phase system is a rotating MMF with a fixed magnitude and direction for every instant. Space vector is a valuable mathematical concept for visualizing the effect of three-phase variables in space. If we supply a current through the winding, which is 120° apart in time, in that case, the current through each of the winding produces its own MMF, which is oscillating in nature. However, the resultant of the three MMF has a fixed magnitude and direction. So it has a fixed magnitude, and it will rotate at the same frequency at which phases are excited. This we know from the basic understanding of electrical machines.

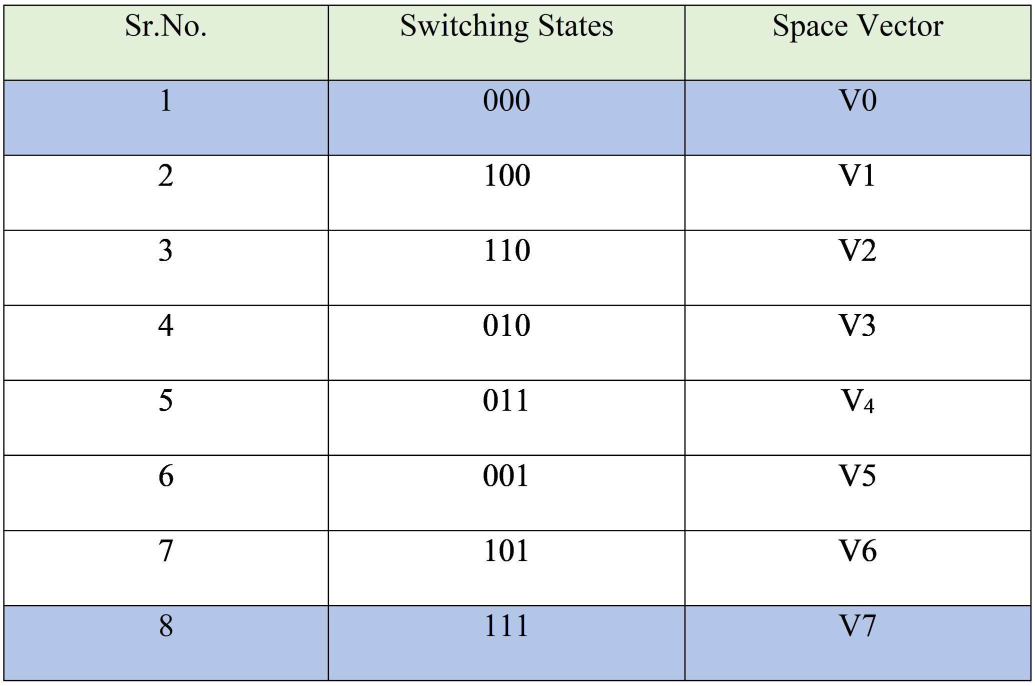
The space vector concept also comes from the idea of rotating MMF. Suppose we see the conceptually, space vector concept for the concept of rotating MMF. In that case, it is very advantageous to have a single quantity representing the three-variation happening in the three phases or in three axes. A space vector is a concept in which we represent three variables by a single space vector. This concept is helpful in many applications. The most valuable application is that we will no longer deal with three different quantities in three different phases. We can represent it by a single quantity, and additionally, it is effortless to visualize a single quantity. For example, we can now easily imagine the machine's resulting air-gap flux. So there is a single quantity rotating in an air gap of the device. But space vector is basically a mathematical concept. For example, the flux in a machine is really a physical quantity residing in the machine's air gap, but a space vector is not necessarily a physical quantity. It is a mathematical concept. The another example, we can define a space vector of voltage and a space vector of current. Still, they are not necessarily a physical quantity represented in an actual space. The following equations show the definition of space vectors. Resultant space vectors for load phase voltage or current are defined in the following equations,

$$V_{R(t)} = \frac{2}{3}[v_{Cn(t)}e^{\frac{j4\pi}{3}} + v_{Bn(t)}e^{\frac{j2\pi}{3}} + v_{An(t)}]I_{R(t)} = \frac{2}{3}[i_{An(t)} + i_{Bn(t)}e^{\frac{j2\pi}{3}} + i_{Cn(t)}e^{\frac{j4\pi}{3}}] \tag{17}$$

$$I_{R(t)} = \frac{2}{3}[i_{An(t)} + i_{Bn(t)}e^{\frac{j2\pi}{3}} + i_{Cn(t)}e^{\frac{j4\pi}{3}}] \tag{18}$$

We define the resultant space vector as the instantaneous magnitudes and the three phases (A, B and C) multiplied by the rotation of these axes into one single phase, and 2/3 is an invariant power transformation. The space vectors $V_{R(t)}$ or $I_{R(t)}$ have both magnitude and angle. Individually voltages/current can be balanced or unbalanced and should not be sinusoidal.

For a converter, we can have a space vector of pole voltages, space vector of line voltages, space vector of load voltages, and space vector of load current, etc. So, the space vector can be any three-phase variable. In converters, we deal with the space vector that we are basically interested in. The voltage space vector is the voltage applied on the load that is VAn VBn and VCn. This is primarily the space vector in which we are interested because this is what we are actually extracting out of the converters and getting on impressing on the load. The pole voltage of one phase of the converter has two switching states:1 (= V_D) and 0 (=0). The upper switch and lower switch are complementary to each other. Since we have three phases, the converter has eight switching states (2x2x2 = 8). These are as follows,Fig. 11



Sr.No.	Switching States	Space Vector
1	000	V0
2	100	V1
3	110	V2
4	010	V3
5	011	V$_4$
6	001	V5
7	101	V6
8	111	V7

Figure 11: Switching States.

Out of these eight switching states, the no.1 & no.8, these are known as zero vectors or states of zero switching. Following example explains the load phase voltage space vector for 100 switching state combination,

$$v_{AO(t)} = V_D \tag{19}$$

$$v_{BO(t)} = 0 \tag{20}$$

$$v_{CO(t)} = 0 \tag{21}$$

Substituting the above values in below equations,

$$v_{An(t)} = \frac{2}{3}v_{AO(t)} - \frac{1}{3}v_{BO(t)} - \frac{1}{3}v_{CO(t)}; v_{An(t)} = \frac{2}{3}V_D \tag{22}$$

$$v_{Bn(t)} = \frac{2}{3}v_{BO(t)} - \frac{1}{3}v_{CO(t)} - \frac{1}{3}v_{AO(t)}; v_{Bn(t)} = -\frac{1}{3}V_D \tag{23}$$

$$v_{Cn(t)} = \frac{2}{3}v_{CO(t)} - \frac{1}{3}v_{AO(t)} - \frac{1}{3}v_{BO(t)}; v_{Cn(t)} = -\frac{1}{3}V_D \tag{24}$$

$$V_{R(t)} = \frac{2}{3}[v_{An(t)} + v_{Bn(t)}e^{\frac{j2\pi}{3}} + v_{Cn(t)}e^{\frac{j4\pi}{3}}]; V_{R(t)} = \frac{2}{3}V_De^{j0} \tag{25}$$

We can derive the resultant space vector in the same way for other combinations. The resultant space vector for all the combinations is shown table below Table 1

Table 1: Inverter's Switching Vectors

Space Vector	State of switch	Resultant space vector $V_R(t)$	
V_0	000	$\vec{V_0} = 0$	Zero Vector
V_1	100	$\vec{V_1} = \frac{2}{3}V_De^{j0}$	Active Vector
V_2	110	$\vec{V_1} = \frac{2}{3}V_De^{j\frac{\pi}{3}}$	Active Vector
V_3	010	$\vec{V_3} = \frac{2}{3}V_De^{j\frac{2\pi}{3}}$	Active Vector
V_4	011	$\vec{V_4} = \frac{2}{3}V_De^{j\frac{3\pi}{3}}$	Active Vector
V_5	001	$\vec{V_5} = \frac{2}{3}V_De^{j\frac{4\pi}{3}}$	Active Vector
V_6	101	$\vec{V_6} = \frac{2}{3}V_De^{j\frac{5\pi}{3}}$	Active Vector
V_7	111	$\vec{V_7} = 0$	Zero Vector

Now we will see switching between the all eight switching states combination. We use one of the very established principles: the volt second balance. The SVPWM is the strategies of switching space vectors so that the resultant voltage or current is realized. So, it is a switching strategy by which we can appropriately switch the vector for specific time durations. In a cycle, the space vectors are switched for a set amount of time to produce the resultant vector. The resultant of the vector is given in the following equation,

$$V_RT_s = V_1T_1 + V_2T_2 + V_0T_0 \tag{26}$$

$$V_RT_s = \ V_1T_1 + \ V_2T_2 + V_0T_{01} + V_0T_{02} \tag{27}$$

$$T_s = T_1 + T_{2+T_0} \tag{28}$$

In space vector PWM,

$$T_{01} = T_{07} = \frac{T_0}{2} \tag{29}$$

V_RT_s is a resultant space vector applied during the time interval or period T_S. We switch the three nearest vectors enclosing the resulting vector to produce the resulting vector. When we go from one switching state to another switching state, there is only a switching transition. In the above equations, it is required to calculate the timing duration to get the resultant voltage. In the above discussion, we said we would switch a vector for the T_1 period, another vector for the T_2 period, and a zero vector for the T_0 period now; we will find out the timing duration. We will calculate the timing duration in the following mathematical expression of timing. Consider sector one; the vector diagram is as follows, Fig.12

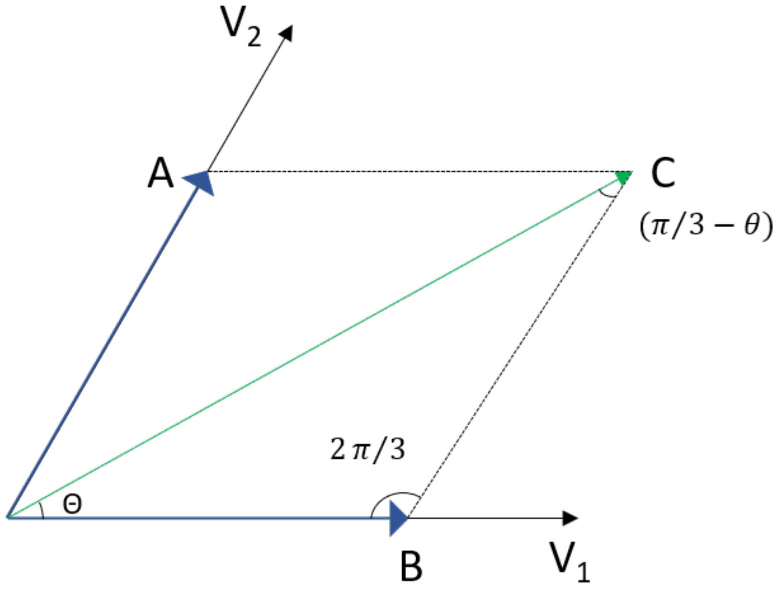


Figure 12: Vectors diagram of sector one

$$\frac{OC}{sin(\frac{\pi}{3}-\theta)} = \frac{OA}{sin\theta} = \frac{OB}{sin(\frac{2\pi}{3})} \text{..............} \textit{By trigonometry.} \tag{30}$$

Applying the V_1 vector for T_1 duration, the net volt second is represented by OC, similarly OB and OA. So,

$$OC = V_1T_1; OB = V_2T_2; OA = V_RT_S \tag{31}$$

$$\frac{V_1T_1}{sin(\frac{\pi}{3}-\theta)} = \frac{V_2T_2}{sin\theta} = \frac{V_RT_S}{sin(\frac{2\pi}{3})} \tag{32}$$

$$T_1 = sin(\frac{\pi}{3}-\theta)\frac{V_R}{V_1}\frac{2}{\sqrt{3}}T_S \tag{33}$$

by putting $V_1 = \frac{2V_D}{3}$

$$T_1 = sin(\frac{\pi}{3}-\theta)\frac{V_R}{V_D}\sqrt{3}T_S \tag{34}$$

$$T_2 = sin\theta \frac{V_R}{V_2} \frac{2}{\sqrt{3}} T_S \tag{35}$$

by putting $V_2 = \frac{2V_D}{3}$

$$T_2 = sin\theta \frac{V_R}{V_D} \sqrt{3} T_S \tag{36}$$

$$T_0 = T_S - T_1 - T_2 \tag{37}$$

Consider $\theta = 0$ and $V_R = \frac{2V_D}{3}$ and put the values in the above equations we get the following values,

$$V_R = \frac{2}{3} V_D \angle 0^\circ \tag{38}$$

$$T_2 = 0 \tag{39}$$

$$T_1 = \sin(\frac{\pi}{3}) \frac{2}{3} \frac{V_D}{V_D} \sqrt{3} T_S \tag{40}$$

$$T_1 = \frac{\sqrt{3}}{2} \frac{2}{3} \sqrt{3} T_S \tag{41}$$

$$T_1 = T_S \tag{42}$$

$$T_0 = 0 \tag{43}$$

From the above example, we can see that throughout the time period T_S only the vector V_1 will be switched. The zero vectors are the V_0 and V_7, and the duration of V_0 and V_7 are kept equal, giving the best harmonic performance. However, for some unique switching sequences like discontinuous PWM, the division is not made equal, and this is done although it will give a poorer harmonic performance. However, it is done to get some other benefits. These benefits are like loss distribution or changing the losses in the switch, in neutral point clamp converter the capacitor voltage balancing and so on. These particular switching sequences are used where the starting and the ending vectors are not of equal duration of time.

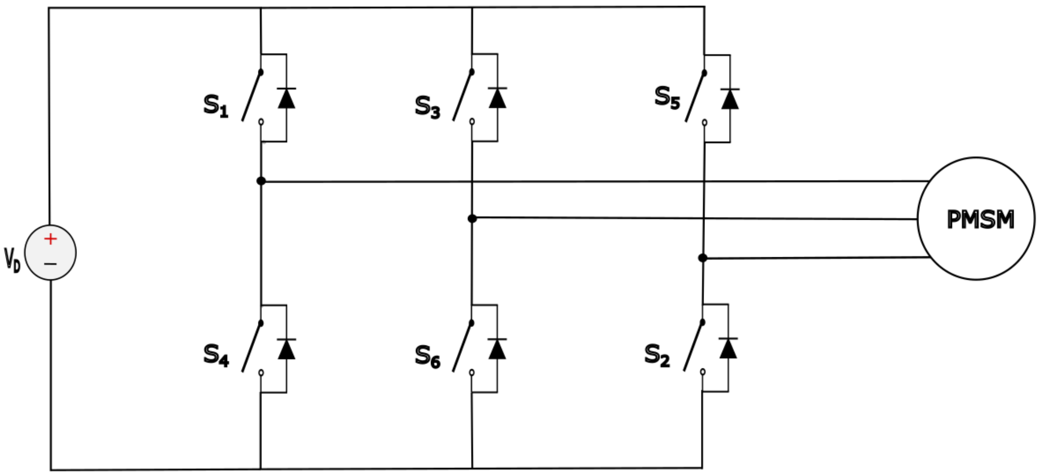
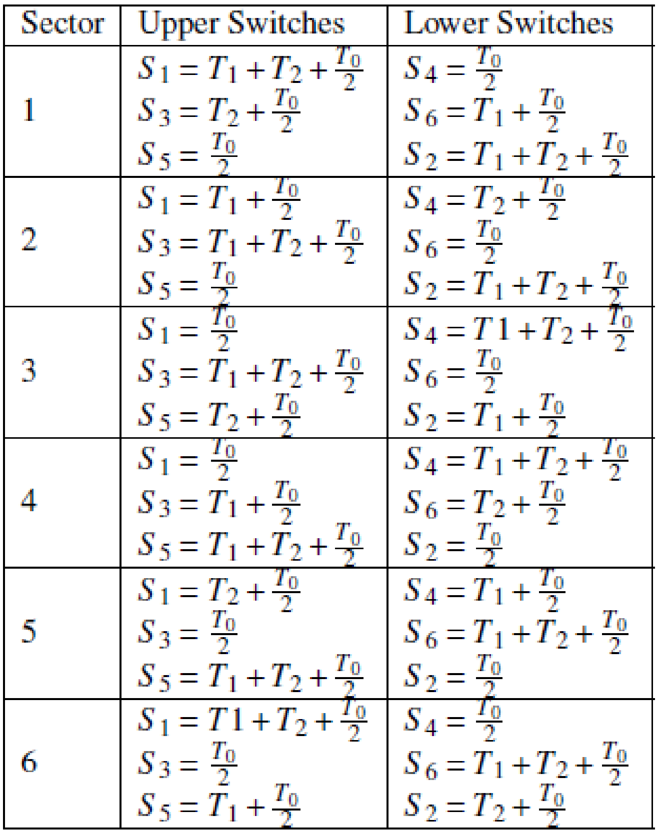


Figure 13: Inverter

The time calculation of switching for each sector is presented in the Fig. 14 below,



Sector	Upper Switches	Lower Switches
1	$S_1 = T_1 + T_2 + \frac{T_0}{2}$ $S_3 = T_2 + \frac{T_0}{2}$ $S_5 = \frac{T_0}{2}$	$S_4 = \frac{T_0}{2}$ $S_6 = T_1 + \frac{T_0}{2}$ $S_2 = T_1 + T_2 + \frac{T_0}{2}$
2	$S_1 = T_1 + \frac{T_0}{2}$ $S_3 = T_1 + T_2 + \frac{T_0}{2}$ $S_5 = \frac{T_0}{2}$	$S_4 = T_2 + \frac{T_0}{2}$ $S_6 = \frac{T_0}{2}$ $S_2 = T_1 + T_2 + \frac{T_0}{2}$
3	$S_1 = \frac{T_0}{2}$ $S_3 = T_1 + T_2 + \frac{T_0}{2}$ $S_5 = T_2 + \frac{T_0}{2}$	$S_4 = T1 + T_2 + \frac{T_0}{2}$ $S_6 = \frac{T_0}{2}$ $S_2 = T_1 + \frac{T_0}{2}$
4	$S_1 = \frac{T_0}{2}$ $S_3 = T_1 + \frac{T_0}{2}$ $S_5 = T_1 + T_2 + \frac{T_0}{2}$	$S_4 = T_1 + T_2 + \frac{T_0}{2}$ $S_6 = T_2 + \frac{T_0}{2}$ $S_2 = \frac{T_0}{2}$
5	$S_1 = T_2 + \frac{T_0}{2}$ $S_3 = \frac{T_0}{2}$ $S_5 = T_1 + T_2 + \frac{T_0}{2}$	$S_4 = T_1 + \frac{T_0}{2}$ $S_6 = T_1 + T_2 + \frac{T_0}{2}$ $S_2 = \frac{T_0}{2}$
6	$S_1 = T1 + T_2 + \frac{T_0}{2}$ $S_3 = \frac{T_0}{2}$ $S_5 = T_1 + \frac{T_0}{2}$	$S_4 = \frac{T_0}{2}$ $S_6 = T_1 + T_2 + \frac{T_0}{2}$ $S_2 = T_2 + \frac{T_0}{2}$

Figure 14: Calculation of Switching Time At Each Sector

Switching frequency is defined as time for which a switch is turned ON first and then turns OFF and turns ON again. During the time period T_s at the time of realizing the vector V_R, that time period T_s is inversely equal to switching frequency of devices. As a result, the higher the switching frequency, the shorter the duration T_s vice versa, higher is the time T_0 lowers will be the switching frequency of the devices.

The voltage equation in frame of abc reference will translated into the frame of stationary reference consisting of the vertical (β) and horizontal (α) axis to implement space vector PWM, providing two 0 vectors and six vectors with non-zero values. Axis of hexagonal shape is formed due to six vectors with non-zero values ($V_6 - V_1$), shown in Fig 9, and provide either a DC connection voltage or electric power to the load. Any two consecutive vectors with non-zero values are placed at 60°apart from each other. At the origin, two 0 vectors (V_7 and V_0) apply no voltage to the load.

To obtain the prefered voltage reference vector V_{ref} in d-q plane, apply the same transformation to prefered voltage output. Purpose of SVPWM strategie is to use the all 8 patterns of switching to get the V_{ref} (voltage of reference vector) [22].

5. SIMULATION

In this simulation, the permanent magnet synchronous machine block configures as a three-phase PMSM. Mechanical torque is an input port of a PMSM, where applied torque decides machine action that is in motor mode or generator mode. The PMSM will act like motor if applied mechanical torque is positive. If we apply a negative torque to the device's shaft, it will serve as a generator. In the PMSM block, select the back EMF as a sinusoidal waveform and rotor type as a round. In this model, a 3kW, 3000rpm PMSM is used. To put all the PMSM parameters in the block, we have to configure the block. For configuration, click on the parameters and go to the tab "compute from standard manufacturer specifications". In this tab, we can put all the motor details, add the remaining parameter, and put the same parameters in the block for simulation. All the detailed specification of the PMSM is mentioned in the following Table 2,

Table 2: PMSM specifications

Parameters	Values
Inductance (L)	1.67 mH
Resistance (R)	0.36 Ω
Torque Constant (kt)	0.428636 N.m/Apeak
Voltage Constant (ke)	51.8307 Vpeak (L-L)/Krmp
Viscous damping (F)	0.000303448 N.m. s
Inertia (J)	0.000621417 (kg.m2)
Pole Pair (p)	3
Armature inductance (H)	835 * 10^{-6} H
Stator phase resistance (Rs)	0.18 Ω
Flux linkage established by magnets	0.0714394 Wb

An inverter is connected to the 400 volts DC supply. A three-phase VSI block is used to change from DC supply into a AC supply (3-phase) for PMSM. The FOC autotuner block is used in MATLAB/SIMULINK to automatically tune the PI controller gains connected in a closed-loop FOC built model using the motor control blockset. We may automatically tune the four control loops in a closed-loop FOC built model using the FOC Autotuner block.

1. Speed loop
2. Flux loop
3. d-axis current loop
4. q-axis current loop

From the above four control loops, we can use whatever we want based on the type of method we choose to control PMSM. In this simulation model, we are using only two control loops first one is the direct-axis (d-axis) current loop, and another one is the speed loop and collecting the gains from the FOC autotuner block. During the autotuning process, the FOC autotuner block injects perturbation signals at the plant inputs connected to each control loop and evaluates the responses at measured feedback for each loop. When the experiment is finished, the block computes the PI gains and returns them to the PI gains port. When the simulation model is not running, the block does not send any perturbation signals. In this state, the block has no effect on plant or controller behaviour. After collecting the PI gains from the PI gains port, we can directly put those gains in the PID controller block and check the machine's response. After reviewing the machine's response, we can remove the FOC autotuner block.

6.1. Step 1 :- Generating SVPWM pluses.

This is the first level for implementation of FOC on the LaunchPad. In this level we will be generating SVPWM signals with the help of MATLAB/ SIMULATION. Following diagram shows the simulation of FOC at level 1 Fig.15.

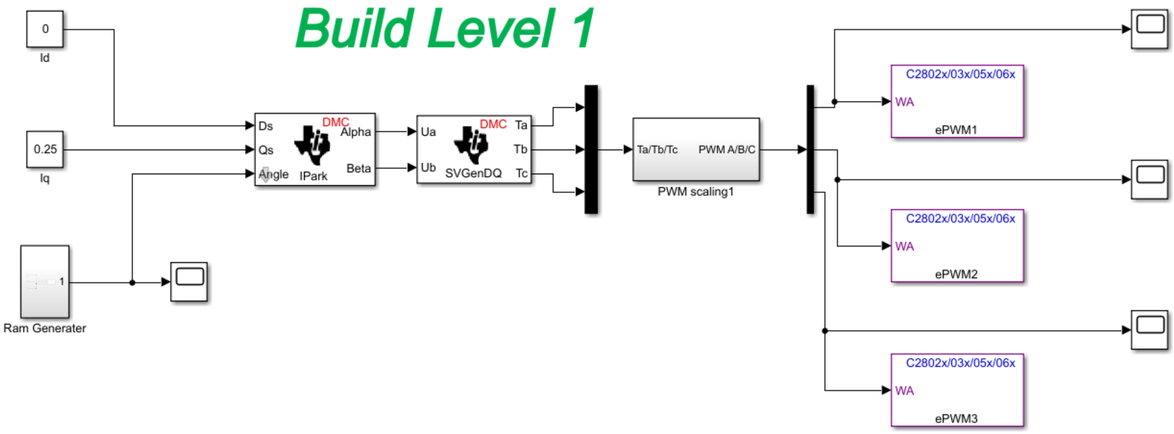


Figure 15: Simulation for generating SVPWM pulses

In this level we consider quadrature axis current as 0 per unit and direct axis current as 0.25 per unit for testing purpose only in final level it will be changed. To provide rotating angle we will be adding ramp generating signals to the Inverse Parks Transformation block to mimic rotating shaft position so that PWM signal should be generated. Ramp generator output is shown in figure below Fig.16.

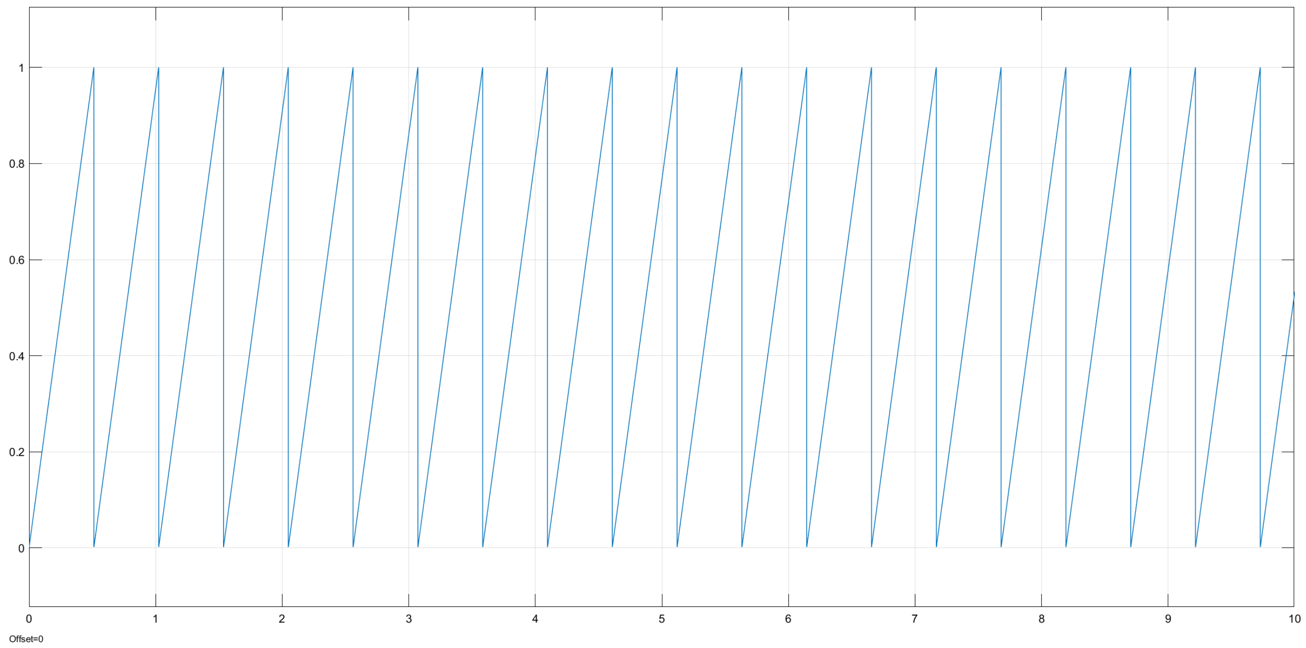


Figure 16: Ramp Generator Output

After giving the above ramp signals to Inverse Parks Transformation block, it generates two signals that is alpha and beta these two outputs are then connected to the Space vector generator block. This block converts vectors from a rotating to a two-phase frame of stationary reference. Park's inverse transformation block uses following equations for implementation,

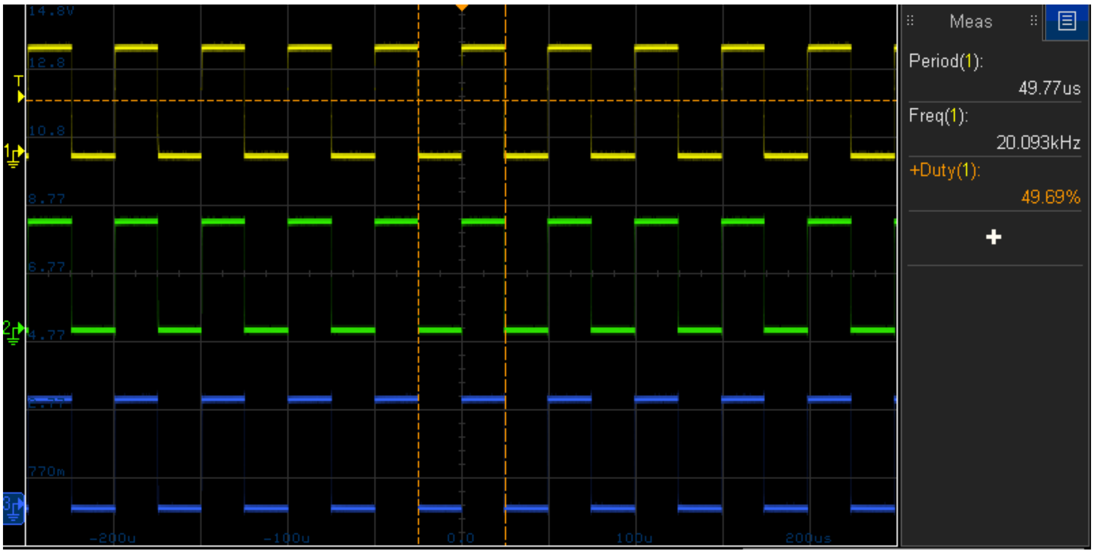
$$I_{alpha} = I_D * cos\Theta - I_Q * sin\Theta \tag{44}$$

$$I_{beta} = I_D * sin\Theta + I_Q * cos\Theta \tag{45}$$

Following the generation of alpha and beta components, these components will now be used as inputs to the space vector generator block. Using the SVPWM approach, this block computes duty ratios that yield a particular stator reference voltage. SVPWM is a switching sequence of a three-phase VSI's upper 3 power switches that is utilised in applications such as AC induction and PMSM drives. In the stator phases, the switching technique produces three phase pseudosinusodial currents. By integrating the switching patterns corresponding to the basic space vector, the approach approximates a particular stator reference voltage. The alpha and beta components are turned into reference phase voltage using the inverse Clark's transformation. These voltages are expressed as PWM duty ratios in the output.

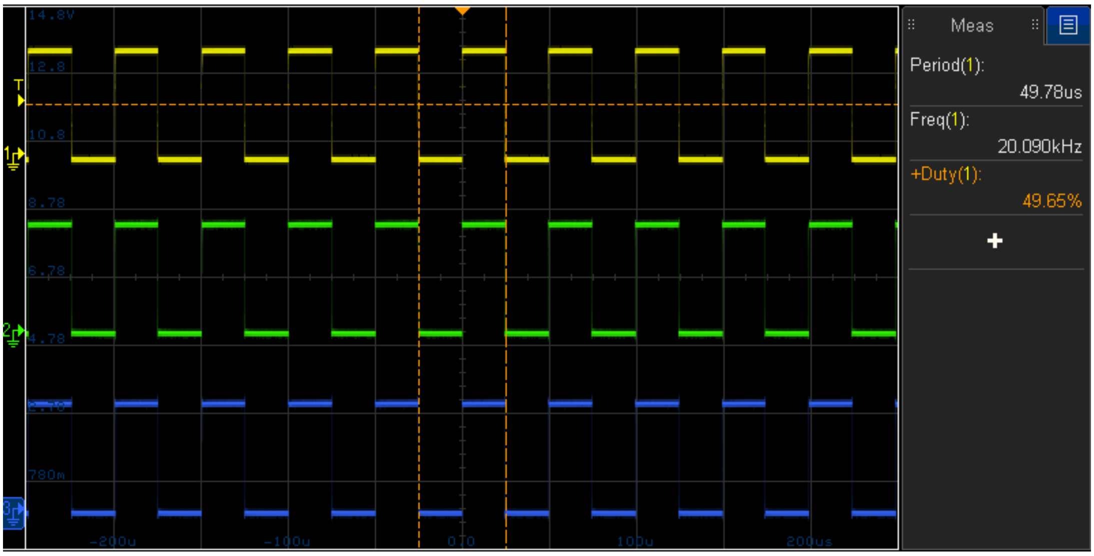
6.1.1. PWM Scaling: -

The voltages computed from the field-oriented control are too high. To fit these high voltages within the PWM carrier wave magnitude range, PWM scaling is required in the hardware implementation. The PWM scaling scales down the voltages computed from the FOC and shifts the negative voltages to the positive level within the PWM carrier wave magnitude range. After PWM scaling the obtained signals are then pass to the ePWM pins of the launchpad. With the help of DSO (Digital Oscilloscope) PWM waveform is observed by connecting jumper wires to the ePWM pins of launchpad. Observed waveform on DSO are shown in the following figure Fig.17 and Fig.18.



Period(1):
49.77us
Freq(1):
20.093kHz
+Duty(1):
49.69%

Figure 17: Output from ePWM pins of LaunchPad.



Period(1):
49.78us
Freq(1):
20.090kHz
+Duty(1):
49.65%

Figure 18: Output from ePWM pins of LaunchPad .

6.2. Step 2 :- Connecting PMSM in open loop and running the motor

To run the motor, we need inverter module and 24V DC supply. Inverter module is connected to the ePWM pins and 24V DC supply is also connected to the inverter module. To start the motor, we have to adjust Idref and Iqref value to overcome the initial motor inertia. In this step we will be adding ADC block to simulation which is useful for current measurements. After taking inputs from ADC pins, for the next build level we have to complete the current loop for that purpose we will calibrate current sensing.

6.2.1. Current Calibration: -

In current calibration, stator phase currents Ia and Ib is measured with the help of current transformer (C.T) and output of the C.T is then given to the ADC pins of launchPad. Depending on the C.T ratio current is calibrated and waveforms are observed on MATLAB/ SIMULATION. Simulation for current calibration is presented in figure below Fig.19

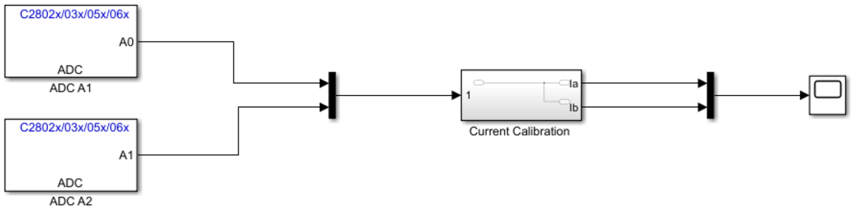


Figure 19: Simulation diagram for current calibration

6.3. Step 3 :-Making PI controller close-loop connections in the current controller.

A calibrated current in previous level is now given to the Clark's transformation block. This block will transform three-phase balanced quant intoity two-phase balanced quadrature quantity. Clark's transformation block uses following equations for implementation,

$$I_d = I_a \tag{46}$$

$$I_q = \frac{2 * I_b + I_a}{\sqrt{3}} \tag{47}$$

After getting the Id and Iq values, these values are then act as an input to the Park's transformation block. This block transform vectors in the frame of stationary reference to a two-phase frame of rotating reference. Parks transformation block uses following equations for implementation,

$$I_d = I_d cos\Theta - I_q sin\Theta \tag{48}$$

$$I_q = I_d sin\Theta + I_q cos\Theta \tag{49}$$

After getting I_d and I_q values from Park's transformation block, these values are passed to PI controllers of I_d and I_q as feedback values. The reference value of I_d is taken as 0 p.u, and for I_q, it is adjusted to 0.25 p.u for the testing purpose. We can get the values of k_p and k_i for both I_d and I_q PI controllers. After putting the gains in the PI controllers, we must ensure that the motor runs satisfactorily with the given gains. The following diagram shows the simulation of close-loop connections of PI controllers in the current controller,

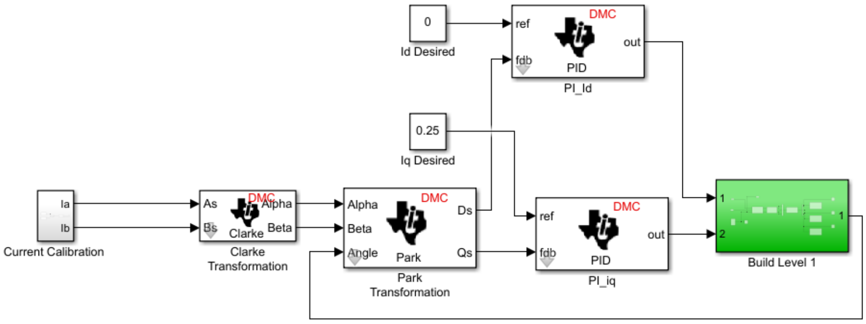


Figure 20: Simulation diagram of close-loop connections of PI controllers in the current controller.

6.4. Step 4 :- Calibration of Encoder.

Encoder resolution is interpreted as the no.of pulses per revolution (PPR) or bits produced by the encoder during a 360° rotation of the encoder shaft. If an encoder doesn't have enough resolution, it will be unable to provide the controller feedback it needs to function correctly. In encoder calibration, we first observe how many counts per electrical revolution or mechanical revolutions a four-pole pair PMSM produces. The encoder calibration block is introduced in the circuit to count the no. of pulses and convert that value to get the position detail. To avoid the error in the readings, an index offset pulse (mentioned in the manufacturer's datasheets) is added to the actual pulses of the encoder, thus compensating for the difference between the actual zero rotor angle and encoder index pulse. After getting the position information, this information is passed to the speed measurement block.

6.5. Step 5 :- Implementing the speed control in the circuit.

The speed measurement block gives the actual speed in RPM by differentiating the position information with respect to the time. This is the last step of the implementation. In this step, we will remove the ramp-generated angle and replace it with the actual angle obtained from the encoder. A low pass filter option is available in the speed measurement block to filter out the position signal if it is noisy. The reference and actual speed are passed to the speed PID controller, which generates the I_q reference current. This I_q current acts as one of the inputs to the current control loop. After connecting the I_q reference current, the PMSM close loop speed control is represented in figure 21 below,

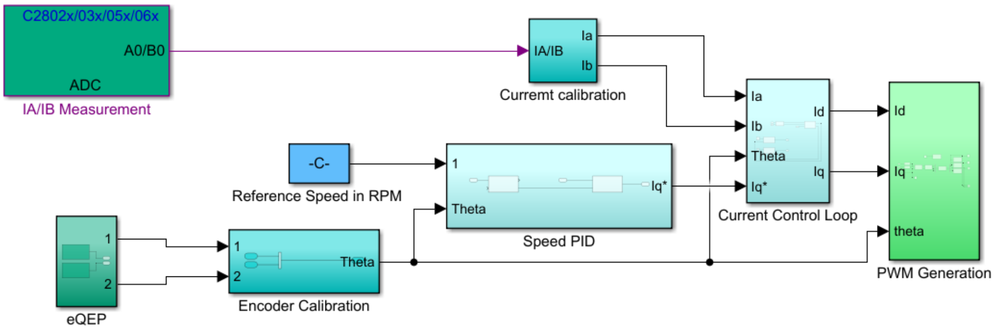


Figure 21: Simulation diagram of Build Level Five.

7. RESULTS AND DISCUSSION

MatLab-Simulink is used to implement the vector control for PMSM drive system. Hardware implementation is studied and implemented up to generating SVPWM pluses on the TI's C2000 F28069M launchpad.

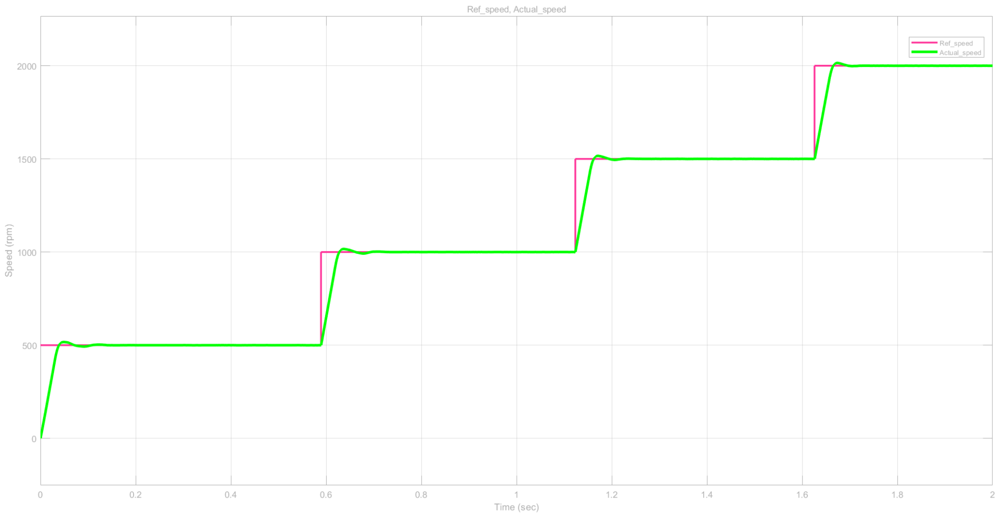
PMSM is an ac motor, and we generated an AC voltage here. In the case of the dc machine, we know that the armature input current flows will generate its own magnetic field, but it does not impact the main magnetic field in the system because they are oriented at different angles. But we can not ensure that there is a rotating magnetic field in the case of an ac machine. How does one ensure that the magnetic field, if we leave it as it is, the magnetic field generated by the flow of current in the stator does not oppose the magnetic field caused by the rotor itself? It has to be explicitly implemented in this case. Therefore, the I_d reference current is taken to zero because we don't want the stator-generated magnetic field to either increase the rotor's magnetic field or decrease the rotor's magnetic field under regular operation.

In this simulation, the following gains are obtained with the help of the FOC autotuner block given in the Table 3 below,

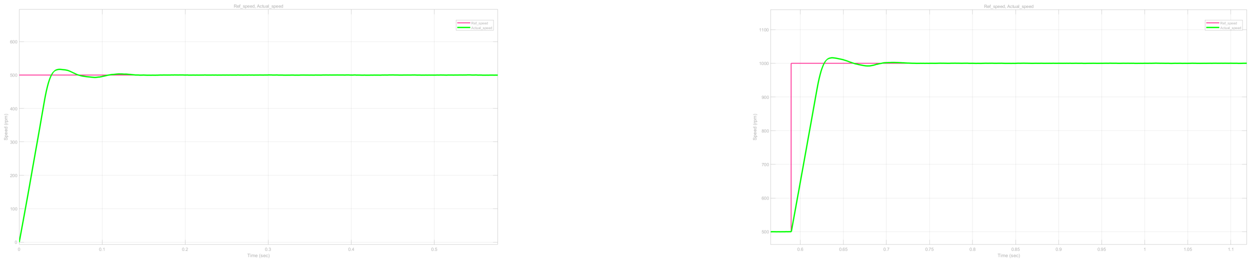
Table 3: Controller Gains

Speed Controller Gains	$K_p = 0.25$ $K_i = 25$
Current Controller Gains	$K_p = 0.2$ $K_i = 10$

In this close loop control, the inverter output frequency is determined by the actual rotor speed. Actual and reference speed difference are fed back to speed controller. The speed response of the PMSM after tuning the PI controllers on no-load Fig.22 and full load Fig.23 is shown below,

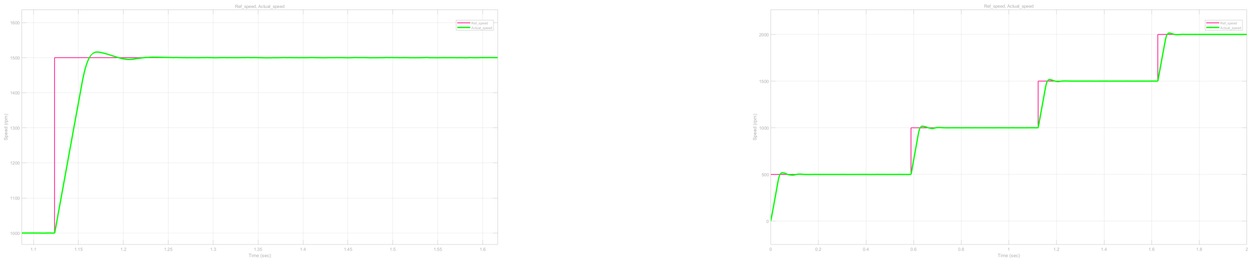


(a) Speed



(b) Zoom view of Speed at starting(500rpm)

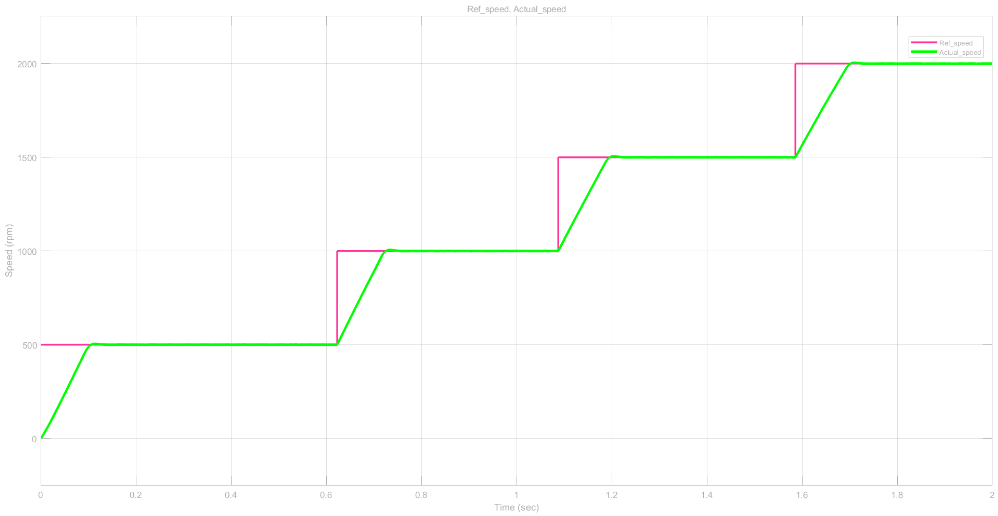
(c) Zoom view of Speed around 0.5 sec(1000rpm)



(d) Zoom view of Speed around 1.0 sec(1500rpm)

(e) Zoom view of Speed around 1.5 sec(2000rpm)

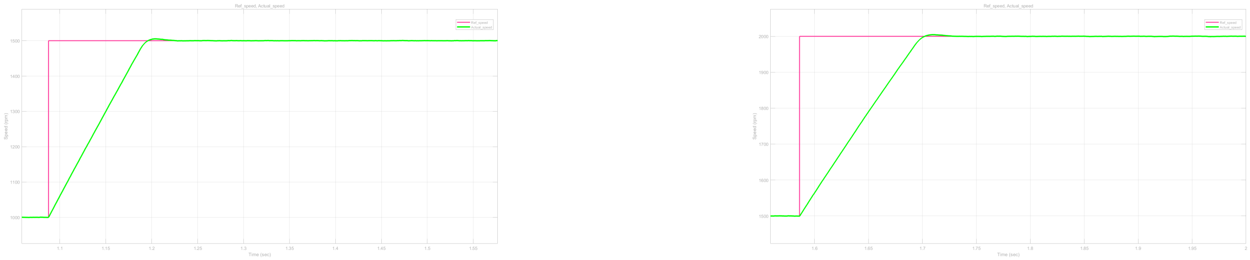
Figure 22: PMSM speed response on no load



(a) Full View of Speed

(b) Zoom view of Speed at start(500rpm)

(c) Zoom view of Speed around 0.5 sec(1000rpm)



(d) Zoom view of Speed around 1 sec(1500rpm)

(e) Zoom view of Speed around 1.5 sec(2000rpm)

Figure 23: PMSM speed response on full load

The VSI’s output phase to phase voltage is depicted in the image 24 and 25 below,

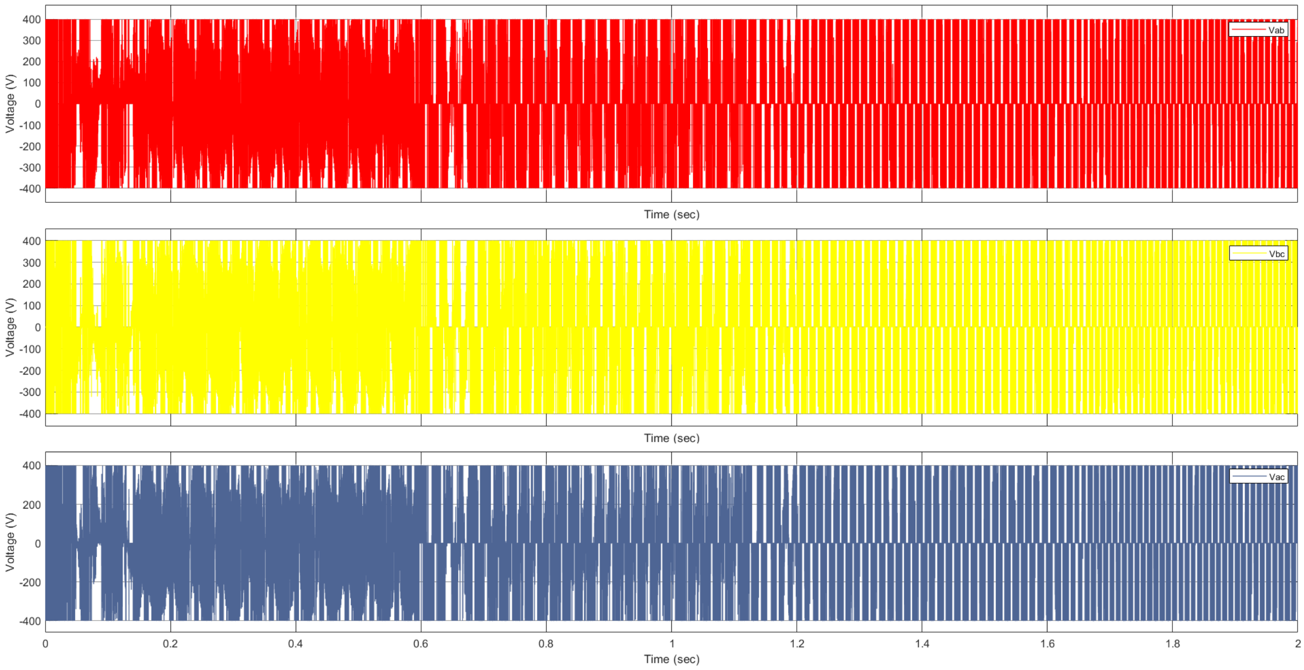


Figure 24: Voltage Source Inverter output voltage

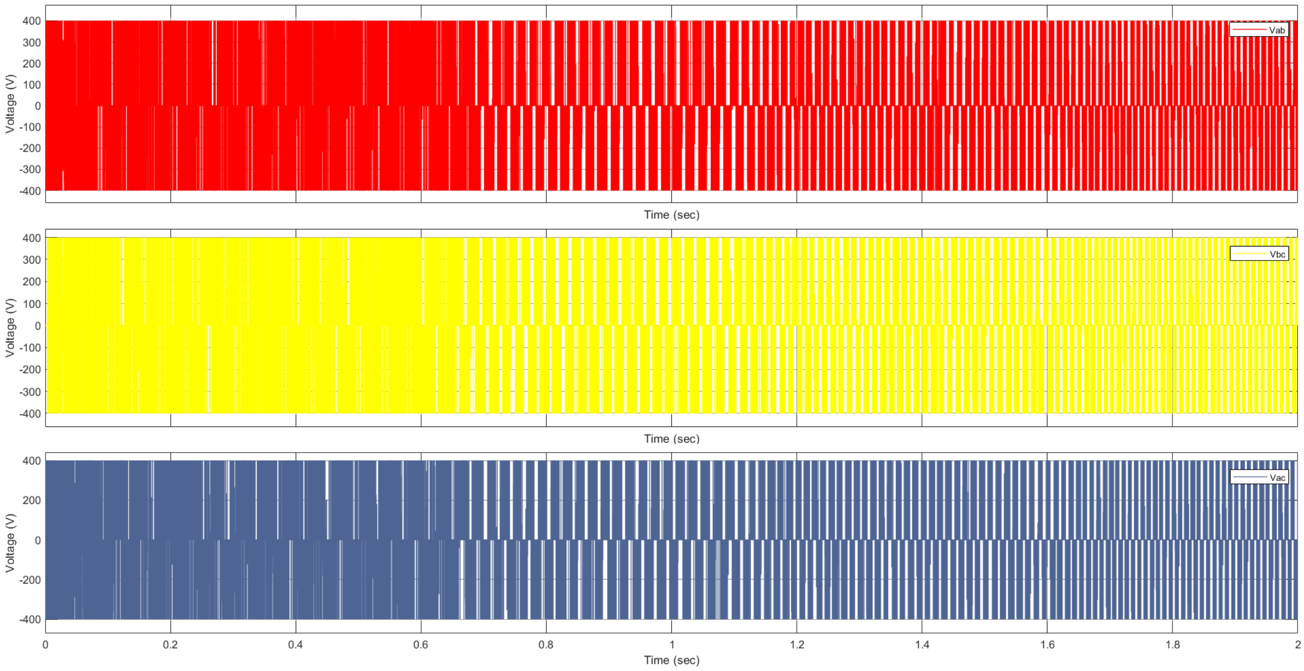


Figure 25: Voltage Source Inverter output voltage at full load

SVPWM is used to create the gate pulses for the VSI. In PMSM block, measurements of motor like rotor angle, stator currents, motor speed, electromagnetic torque, and other machine quantities are given. The rotor angle and measured speed are used for field-oriented control. The measured speed from the motor is in radian per second, so to convert speed into rpm, we have to add a constant gain of 9.548 at the output of the measured motor speed. After getting the speed in rpm, this speed is called actual/measured speed. The error signal is generated by subtracting actual/measured speed from references/desired speed. The PI controller is then connected to this error signal, and gains are adjusted with the help of FOC Autotuner block. The connecting diagram of FOC Autotuner block in closed-loop FOC stucture is shown in the following Figure 26,

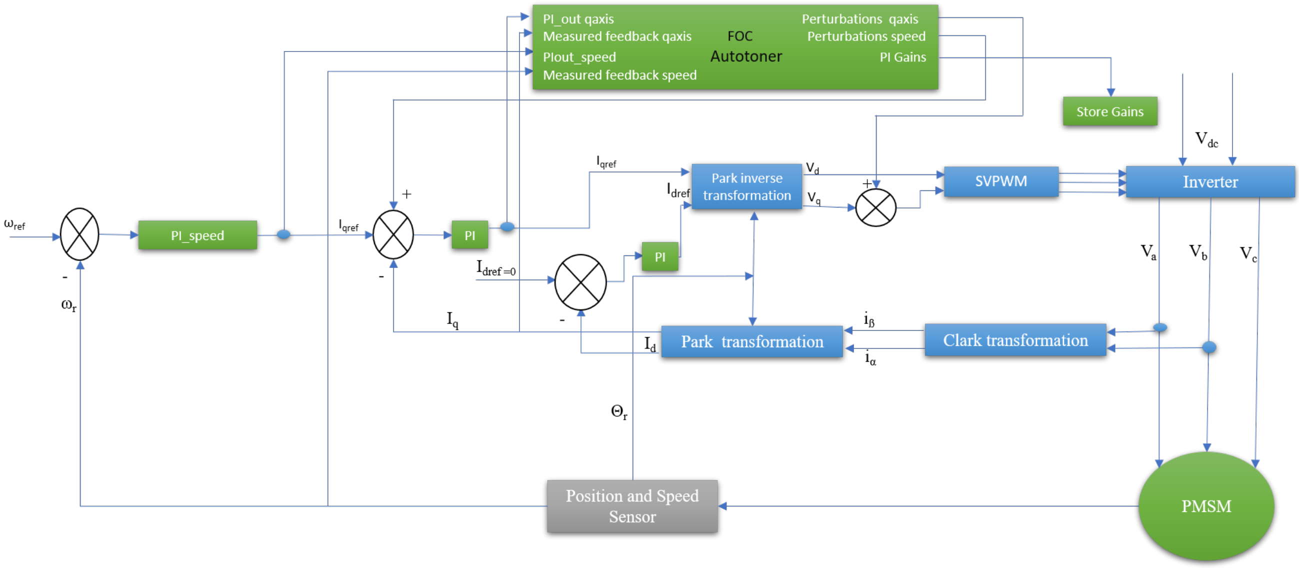
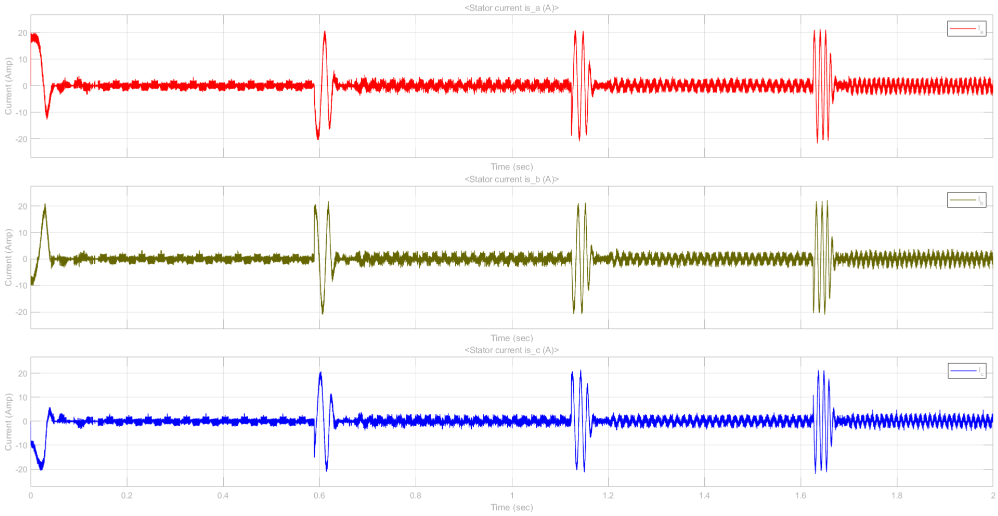


Figure 26: Connection of FOC Autotuner Block in closed-loop FOC stucture

The change in amplitude and change in the frequency with respect to the change in speed of the stator current on no load Fig.27 and full load Fig. 28 are shown in the following figures.



(a) Full View of Stator Current

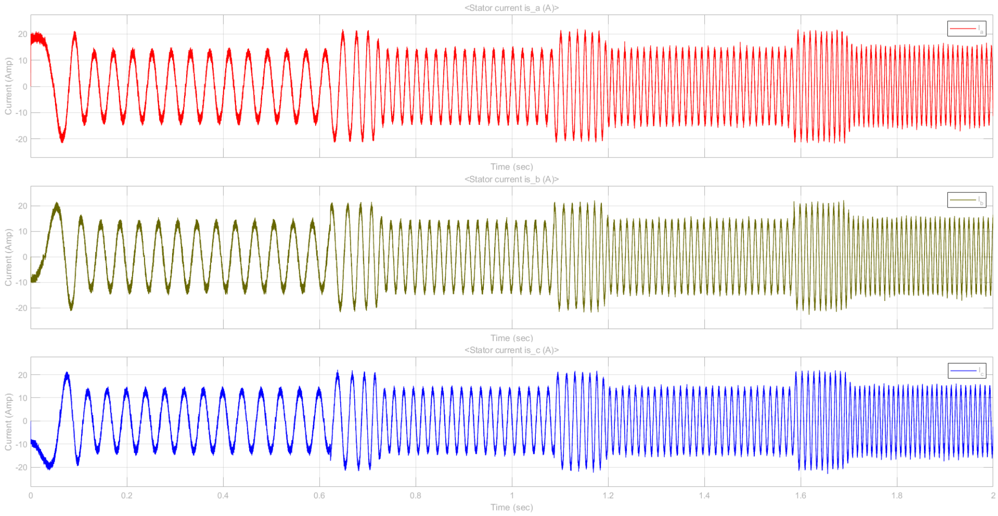
(b) Zoom view of Stator Current at start

(c) Zoom view of Stator Current around 0.5 sec

(d) Zoom view of Stator Current around 1 sec

(e) Zoom view ofStator Current around 1.5 sec

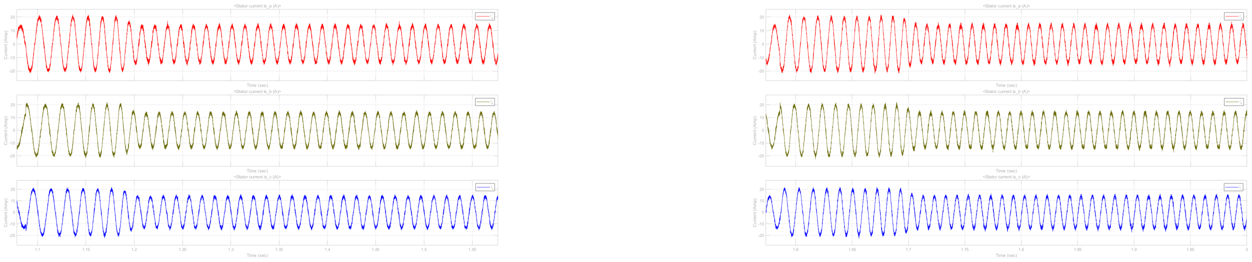
Figure 27: Stator current on No Load



(a) Full View of Stator Current

(b) Zoom view of Speed at start

(c) Zoom view of Speed around 0.5 sec



(d) Zoom view of Speed around 1 sec

(e) Zoom view of Speed around 1.5 sec

Figure 28: Stator current on Full Load

8. CONCLUSIONS AND FURTHER WORK

This thesis presented a FOC algorithm for speed control of a PMSM using the MATLAB-Simulink software environment. The implementation of the FOC algorithm is presented up to the generation of SVPWM pluses using MATLAB Embedded coder package and TI's C2000 F28069M launchpad. After applying the FOC algorithm, the drive's performance is observed, and results are added. The control of speed over the entire range is smooth. As the hardware implementation utilizes components from the MATLAB package of embedded coder, this will be simpler than implementing the FOC algorithm using C programming in Code Composer Studio.

To further enhance the performance of the speed controller, the SVPWM used in operation should be greater than the 2-level SVPWM. The development of the FOC autotuner block and multilevel SVPWM block in the MATLAB embedded coder package is needed. It will ease the researcher's work on the controller part and get accurate gains.

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