Torque Ripple Reduction in Three-Phase Four-Switch Inverter-Fed PMSM Drives Using Space Vector Pulse-Width Modulation

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Master in Electrical Engineering

Submitted by

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CERTIFICATE

This is to certify that the thesis entitled **"Torque Ripple Reduction in Three-Phase Four-Switch Inverter-Fed PMSM Drives Using Space Vector Pulse Width Modulation**" submitted by **UJJWAL MONDAL** (Examination Roll No: **M4ELE24003B**, under our supervision and guidance during the session of 2022-24 in the department of Electrical Engineering, Jadavpur University. We are satisfied with his work, which is being presented for the partial fulfilment of the degree of **Master in Electrical Engineering** from Jadavpur University, Kolkata-700032.

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ABSTRACT

This thesis focuses on the torque ripple reduction in three-phase four-switch (TPFS) inverter-fed permanent magnet synchronous motor (PMSM) drives using space vector pulse width modulation (SVPWM) techniques. TPFS inverters, known for their reduced switch count and cost-effectiveness, often suffer from increased torque ripples, which can degrade the performance and reliability of PMSM systems. The study addresses both low- and high-frequency torque ripples, analysing the effects of DC-link voltage fluctuations and harmonics. A novel approach utilizing non-orthogonal coordinate transformation to minimize second-order torque harmonics resulting from fluctuations in DC capacitor voltage.

The thesis also examines various SVPWM methods to find the best one for reducing high-frequency torque ripple, measuring the effectiveness by using the root-mean-square value of the torque ripple.

An adaptive capacitor voltage offset suppression method is introduced to fully exploit the available DC-link voltage. Experimental results validate the proposed methods, demonstrating significant improvements in torque ripple reduction and overall system performance.

Keywords–*Capacitor voltage fluctuation, Permanent magnet synchronous motor (**PMSM**) drives, Space vector pulse width modulation (**SVPWM**), Three-phase four-switch (**FSTPI**) inverter, Torque ripple reduction, Field oriented control(**FOC**).*

CONTENTS

CHAPTER-1

INTRODUCTION

Permanent Magnet Synchronous Motors (PMSMs) are increasingly utilized in various industrial applications due to their high efficiency, compact design, and reliable performance. These motors exhibit a high torque-to-weight ratio, operate with minimal noise, and have an inherently high power factor. The use of permanent magnets on the rotor eliminates the need for brushes or slip rings, reducing mechanical losses and maintenance requirements. Speed control in PMSMs is typically achieved through Pulse Width Modulation (PWM) techniques, often in conjunction with advanced control methods such as Field-Oriented Control (FOC) to ensure precise speed and torque regulation. PMSMs are widely adopted in applications such as electric vehicles, industrial automation, and renewable energy systems due to their superior performance and long operational life.

However, despite the many advantages of Permanent Magnet Synchronous Motor (PMSM) drives, one of the main concerns is their high cost. This is largely due to the use of expensive rare-earth magnets and complex control systems. To reduce costs, research has focused on improving the inverter design. One solution is to reduce the number of power switches from the standard six-switch inverter to a more affordable four-switch version. This change can be made without significantly affecting the motor’s performance by using advanced control methods that take advantage of the PMSM's natural characteristics.

The Four-Switch Three-Phase Inverter (FSTPI) employed with Permanent Magnet Synchronous Motors (PMSMs) presents several challenges in comparison to the conventional six-switch inverter. A primary concern is the risk of unbalanced voltage and current across the motor phases, which can lead to uneven torque output and adversely affect overall performance. This imbalance arises from the reduced number of switches, which complicates the effective control of the motor phases. Furthermore, FSTPI systems necessitate the implementation of more sophisticated control strategies, such as Space Vector Pulse Width Modulation (SVPWM), to mitigate these issues and maintain smooth operational performance. Despite these challenges, FSTPIs remain attractive due to their reduced cost and simpler design, making them a viable option for various applications.

In Permanent Magnet Synchronous Motor (PMSM) drives, torque ripples are a major issue that can cause unwanted noise, vibrations, and even shaft failures. To improve performance, several techniques have been developed to reduce these torque ripples.

For example, motor design methods like skewing the rotor, using fractional slot pitch winding, and optimizing magnetic design help decrease cogging torque. Additionally, active control methods such as repetitive control and self-adaptive control address the pulsating torque caused by harmonics in the back electromotive force (back-EMF).

The non-sinusoidal voltages from the converters also create high-frequency torque harmonics, which are affected by the chosen voltage vectors during switching. Researchers have proposed using extra active voltage vectors and optimizing their timing during the switching period to further reduce torque ripples in direct-torque-controlled PMSM drives.

In Three-Phase six switch Inverter (TPSS) fed Permanent Magnet Synchronous Motor (PMSM) drives, the neutral point voltage of the DC bus remains constant, which does not affect the torque performance. Conversely, in Four-Switch Three-Phase Inverter (TPFS) fed PMSM drives, one phase of the stator current flows directly to the midpoint of the split DC capacitors. This configuration leads to periodic fluctuations in the capacitor voltages, which can impact the overall performance and stability of the drive system.

A brief over view of the chapters discussed in this thesis is given below.

Chapter 1 introduces the project, highlighting the significance of utilizing a Four-Switch Three Phase Inverter (FSTPI) for Permanent Magnet Synchronous Motor (PMSM) drives. The chapter discusses the advantages of this inverter topology, including its reduced cost and simpler design compared to the conventional six-switch inverters. It also addresses the key challenges associated with Four-Switch Inverter-fed PMSM drives.

Chapter 2 presents a detailed review of the previous work conducted in the area of Four-Switch Three-Phase Inverter (FSTPI) based Permanent Magnet Synchronous Motor (PMSM) drives. This chapter also discusses the limitations and challenges associated with conventional FSTPI-based PMSM drives. These drawbacks are identified as key factors that motivate the research and development of the proposed solutions in this project.

Chapter 3 discusses the fundamental working principle of a three-phase Permanent Magnet Synchronous Motor (PMSM), including its construction, characteristics, and various applications. The chapter further elaborates on the theory behind closed-loop control for speed regulation, detailing the key aspects and control strategies used to ensure precise motor performance in various operating conditions.

Chapter 4 discusses the fundamental working principle of conventional Six-Switch Inverter based PMSM motor drive, including its construction, voltage vectors, switching Patterns.

Chapter 5 discusses the fundamental working principle of Four-Switch Inverter (FSTPI) based PMSM motor drive, including its construction, voltage vectors, switching Patterns, different modes of operation, their space vector representation.

Chapter 6 Four-switch three phase inverter (FSTPI) based PMSM drives, their design, working principle, open loop control, close loop control.

Chapter 7 discusses the FOC-based SVPWM of FSTPI-Fed PMSM Drive with Capacitor Voltage Offset Suppression, design and implementation.

Chapter 8 discusses the MATLAB Modelling of FSTPI-Fed PMSM Drive Systems

Chapter 9 discusses the experimental results of the Simulation and Conclusion.

Chapter 10 lists the future scope of work that may be done in the proposed drive system for better performance.

CHAPTER-2

MOTIVATION OF THE PROJECT

2.1. BACKGROUND OF THE PROJECT

In the case of a three-phase Permanent Magnet Synchronous Motor (PMSM), conventional analysis indicates that all three phases are actively engaged in generating the rotating magnetic field necessary for smooth motor operation throughout the entire electrical cycle. However, the adaptation of a four-switch inverter topology, wherein one phase (typically phase a) is directly connected to the midpoint of the DC bus, introduces specific challenges. This arrangement leads to an asymmetric voltage vector space, as certain voltage vectors, which would otherwise modulate phase C, become unavailable. The absence of these vectors during Space Vector Pulse Width Modulation (SVPWM) results in uncontrolled voltage states and induces current distortions, causing deviations from the ideal sinusoidal current waveform.

To address these challenges, a novel current-controlled PWM technique was developed, enabling precise, independent control of the currents in the active phases. By carefully modulating the input voltage, this method effectively restores balanced current flow, reduces waveform distortion, and ensures efficient torque production. This technique, which is elaborated upon in subsequent chapters, fulfils the critical requirement for enhanced current control in four-switch inverter-fed PMSM drives, thereby improving overall drive performance and minimizing current ripple.

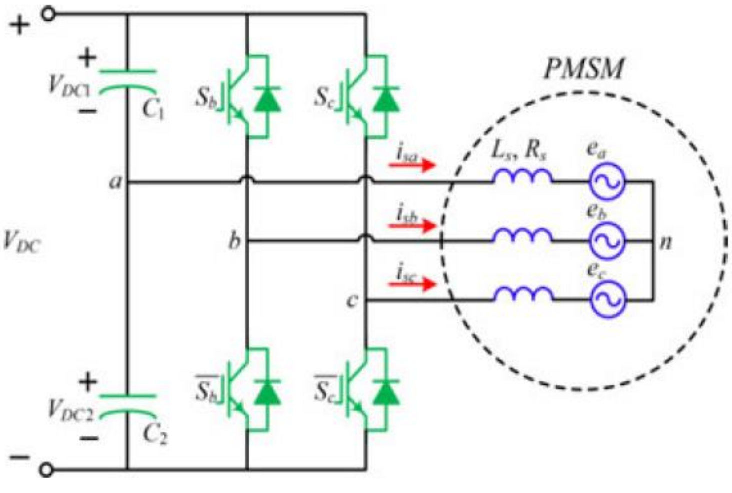


Figure 2.1: Uncontrolled current flow through phase a.

2.2 Drawbacks of the Four-Switch Three-Phase Inverter-Based PMSM Motor Drive

The four-switch three-phase inverter (FSTPI) configuration is an economical alternative to the conventional six-switch three-phase inverter (SSTPI) for Permanent Magnet Synchronous Motor (PMSM) drives. Despite its cost-effectiveness and simplicity, the FSTPI has certain inherent drawbacks that impact the performance and efficiency of PMSM drives.

Some of the key limitations are outlined as follows:

1. **Torque Ripple and Harmonic Distortion**: The FSTPI configuration often exhibits higher torque ripple compared to the SSTPI. The reduction in the number of switches limits the flexibility of the switching patterns, leading to increased harmonic distortion in the motor currents. This distortion directly contributes to torque ripple, which adversely affects the smoothness of motor operation, especially at low speeds or under dynamic load conditions.

2. **Reduced Voltage Utilization**: In FSTPI-based systems, the achievable output voltage is limited compared to SSTPI systems. Since only four switches are used instead of six, the system operates with a reduced number of space vectors. Consequently, the available output voltage range is restricted, leading to lower efficiency and performance in applications that require a high-voltage range or a broad speed spectrum.

3. **Imbalanced Current Flow**: The FSTPI's asymmetrical structure can lead to imbalanced phase currents. This imbalance often results in unequal heating in the windings and adversely affects the motor's lifespan and reliability. The uneven distribution of currents also complicates the control strategy required to maintain performance levels close to those of SSTPI-based systems.

4. **Limited Fault Tolerance**: The FSTPI has reduced fault tolerance compared to the SSTPI. With only four switches, there is limited redundancy in case of failure of one or more switches, which can lead to a complete shutdown of the drive system. This drawback makes the FSTPI less suitable for applications requiring high reliability or safety-critical performance.

5. **Complex Control Requirements**: The unique constraints imposed by the FSTPI topology demand more sophisticated control strategies to achieve

desirable performance levels. Advanced control techniques, such as Space Vector Pulse Width Modulation (SVPWM), are essential for optimizing the inverter's operation. However, implementing such control methods adds to the computational complexity and increases the processing requirements, offsetting the cost savings from using fewer switches.

These limitations underscore the need to explore optimization methods like using Space Vector Pulse Width Modulation to improve FSTPI-based PMSM drive's performance. Reducing torque ripple and enhancing efficiency could make FSTPI a more viable, cost-effective solution in diverse applications, providing a strong motivation for your thesis work on optimizing torque ripple reduction.

2.3 Objectives of the Study

The primary objectives of this study on Permanent Magnet Synchronous Motor (PMSM) drive systems are as follows:

- To analyse the performance of PMSM drives with a Four-Switch Three-Phase Inverter (FSTPI)

- To investigate methods for reducing torque ripple in PMSM drives Examine factors contributing to torque ripple and explore techniques for its minimization to improve drive stability and performance.

- To implement and optimize Space Vector Pulse Width Modulation (SVPWM), Apply SVPWM as a control strategy within FSTPI to enhance torque control, reduce current harmonics, and improve overall drive efficiency.

- To compare FSTPI-based PMSM drive performance with conventional six-switch inverter configurations

- To validate findings through simulation and experimental analysis

CHAPTER-3

PERMANENT MAGNET SYNCHRONOUS MOTOR

3.1 Operational Insights into Three-Phase Permanent Magnet Synchronous Motors: Design, Characteristics, and Closed-Loop Speed Control Strategies

The electric motors are electromechanical machines, which are used for the conversion of electrical energy into mechanical energy. The foremost categories of AC motors are Asynchronous and Synchronous motors. The Asynchronous motors are called singly excited machines i.e. the stator windings are connected to AC supply whereas the rotor has no connection from the stator or to any other source of supply. The power is transferred from the stator to the rotor only by mutual induction, owing to which the asynchronous motors are called as induction machines.

The synchronous motors require AC supply for the stator windings and DC supply for the rotor windings. The motor speed is determined by the AC supply frequency and the number of poles of the synchronous motor, the rotor rotates at the speed of the stator revolving field at synchronous speed , which is constant.

One of the types of synchronous motor is the PMSM. The PMSM consists of conventional three phase windings in the stator and permanent magnets in the rotor. The purpose of the field windings in the conventional synchronous machine is carried out by permanent magnets in PMSM.

The conventional synchronous machine requires AC and DC supply, whereas the PMSM requires only AC supply for its operation. One of the greatest advantages of PMSM over its counterpart is the removal of dc supply for field excitation.

3.2 Permanent Magnet Materials

In modern years, new magnet materials like as Samarium Cobalt (SmCo) First generation rare earth magnet, Strontium Ferrite or Barium Ferrite (Ferrite), Aluminium Nickel and Cobalt alloys (ALNICO), and Neodymium Iron-Boron (Second generation rare earth magnet) (NdFeB) are used for making permanent magnets.

The flux density versus magnetizing field for the above magnets is shown in

Figure 3.1.

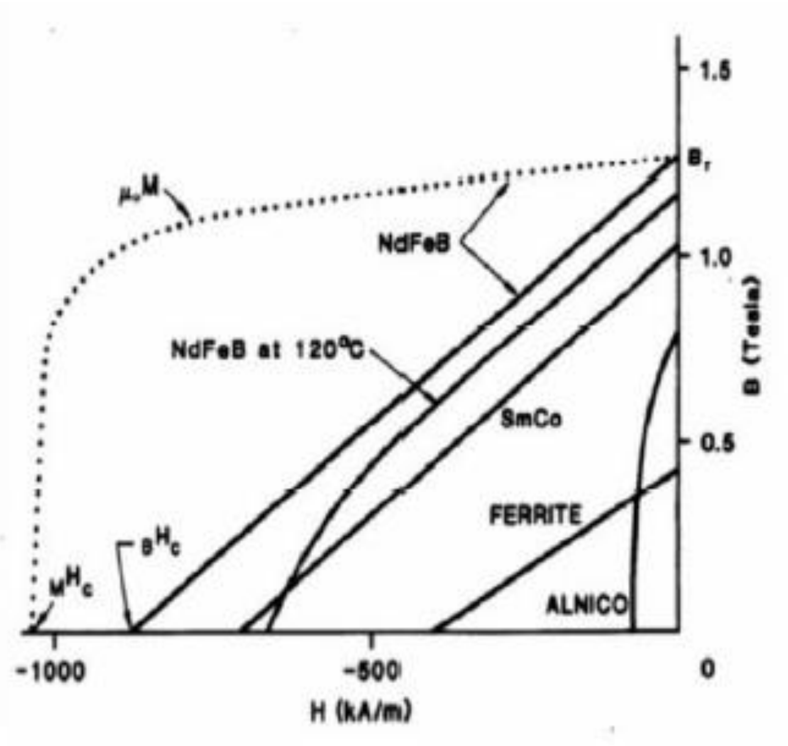


Figure 3.1 Flux Density (B) Versus Magnetizing Field (H) of Different Permanent Magnetic Materials

The Figure 3.2 shows a hysteresis (B-H) curve of a permanent magnet material suitable for PM machines.

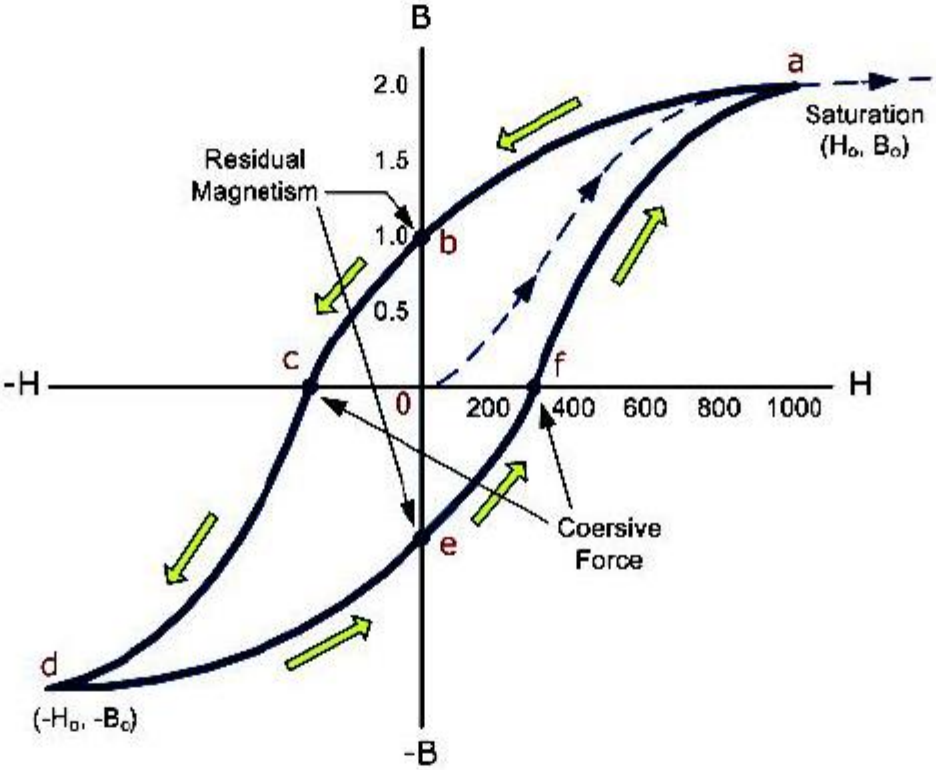


Figure 3.2 B-H Curve of Permanent Magnet Material

3.3 Synchronous Motor and Permanent Magnet Synchronous Motor

When the synchronous machine is excited with a three phase AC supply, a magnetic field rotates at synchronous speed develops in the stator. The synchronous speed of this rotating magnetic field is shown by the Equation (2.1).

$$N_S = \frac{120 * f_S}{P} \text{ rpm} \tag{2.1}$$

Where, N_S - Synchronous speed,

f_S - Frequency of AC supply in Hz,

P - Number of poles,

p - pole pairs and it is given by(P/2).

3.3.1 Classification of Synchronous A.C. Motors

The synchronous AC motors are classified into a number of different types based on its construction and working. The following are the different types of synchronous motors.

- Salient pole
- Non salient pole (round or cylindrical rotor)
- Permanent magnet (surface, inset, buried/interior, imprecated rotor)
- Reluctance motor (synchronous reluctance, switched reluctance)
- Stepping motor (variable reluctance, permanent magnet, hybrid)

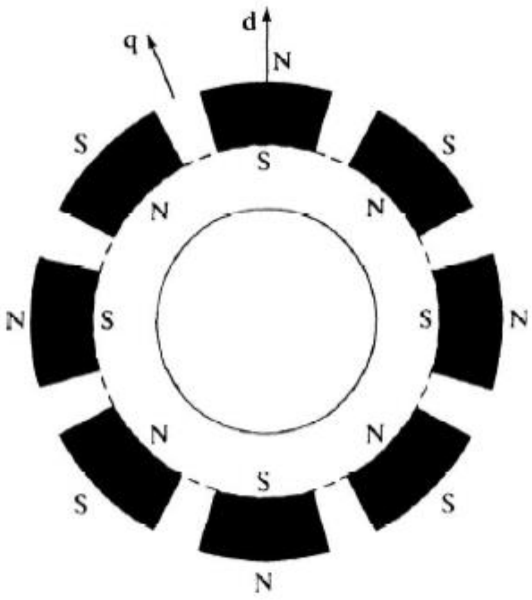
3.3.2 Types of PMSM

The PMSM are classified based on the direction of field flux are as follows,

1. Radial field
2. Axial field

In radial field, the flux direction is along the radius of the machine. The radial field permanent magnet motors are the most commonly used. In axial field, the flux direction is parallel to the rotor shaft. The axial field permanent magnet motors are presently used in a variety of numerous applications because of their higher power density and quick acceleration.

Figures 3.3 and 3.4 shows the permanent magnets mounted on the surface of the outer periphery of rotor laminations. This type of arrangement provides the highest air gap flux density, but it has the drawback of lower structural integrity and mechanical robustness. Machines with this arrangement of magnets are known as Surface mount PMSMs.



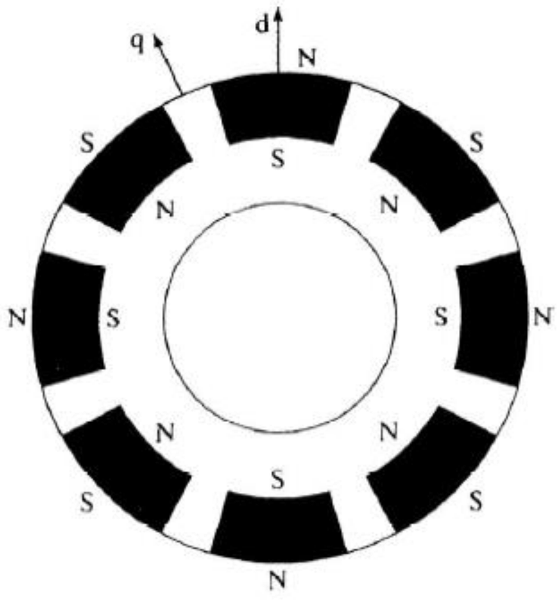
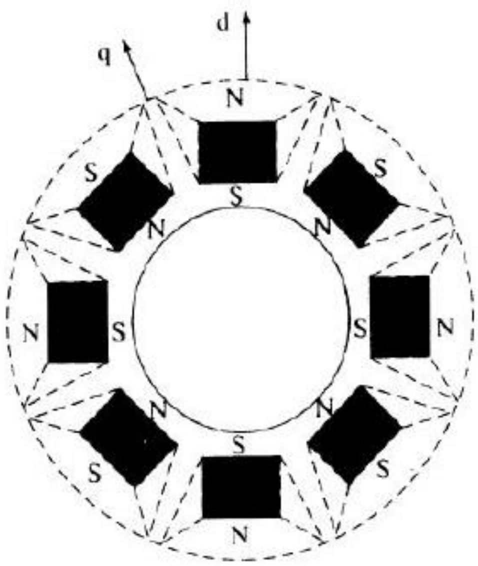


Figure 3.3 Surface Permanent Magnet

Figure3.4 Surface Inset Permanent Magnet

One other types of placing the permanent magnets in the rotor, is embedding the permanent magnets inside the rotor laminations. This type of machine construction is generally referred to as Interior PMSM and it is shown in the Figures 3.5 and 3.6.



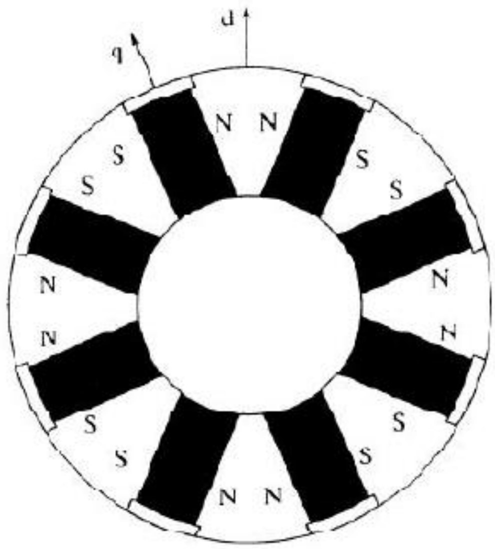


Figure 3.5 Interior Permanent Magnet

Figure 3.6 Interior Permanent with Circumferential Orientation Magnet

The development of this arrangement is more difficult than the surface mount or inset magnet permanent magnet rotors. The inset permanent magnet rotor construction has the advantages of both the surface and interior permanent magnet rotor arrangements by easier construction and mechanical robustness, with a high ratio between the quadrature and direct-axis inductances, respectively.

The surface PMSM with radial flux are generally applied for applications which require low speed operations. These machines have the advantage of high power density than the other types of PMSM. The interior PMSM are used for applications which require high speed.

The principle of operation is identical for all the types of PMSM, in spite of the types of mounting the permanent magnets in the rotor.

3.4.Dynamic Model of PMSM

The dynamic model of PMSM in d-q reference frame can be represented as The model of PMSM is developed on rotor reference frame conventionally known as d-q reference frame using considering assumptions as :

- Saturation is neglected although it can be taken into account by parameter changes.
- The induced EMF is sinusoidal.
- Eddy currents and hysteresis losses are negligible.
- There are no field current dynamics.
- There is no cage on the rotor.

$$V_d = R_S i_d + L_d \frac{di_d}{dt} - \omega_e \psi_q \qquad (2.2)$$

$$V_q = R_S i_q + L_q \frac{di_q}{dt} + \omega_e \psi_d \qquad (2.3)$$

The expression for the fluxes in d-q axes is as,

$$\psi_d = L_d i_d + \psi_m \qquad (2.4)$$

$$\psi_q = L_q i_q \qquad (2.5)$$

The electromagnetic torque is,

$$\tau_e = \frac{3}{2} p[\psi_d i_q - \psi_q i_d] \qquad (2.6)$$

Substituting ,ψ_q and ψ_d one can get,

$$\tau_e = \frac{3}{2} p[\psi_m i_q + (L_d - L_q) i_d i_q] \qquad (2.7)$$

For the surface mounted PMSM , $L_d = L_q$, then the simplified torque equation becomes,

$$\tau_e = \frac{3}{2} p \psi_m i_q \qquad (2.8)$$

Where, p is the number of pole pairs and other notation are conventional.

ω_m is the rotor mechanical speed .Now ω_e being rotor electrical speed , ω_m and ω_e are related as,

$$\omega_e = p\omega_m \qquad (2.9)$$

The mechanical torque equation is expressed as,

$$\tau_e = \tau_L + \beta\omega_m + J\frac{d\omega_m}{dt} \qquad (2.10)$$

And the flux angle is ,

$$\theta = \tan^{-1}(\frac{\psi_q}{\psi_d}) \qquad (2.11)$$

The mechanical speed and rotation angle are as,

$$\omega_e = \int(-\frac{B}{J}\omega_e + \frac{p}{J}(\tau_e - \tau_L))dt \qquad (2.12)$$

$$\frac{d(\theta)}{dt} = \omega_e \qquad (2.13)$$

3.5. Permanent Magnet Synchronous Motor Drive System

The motor drive essentially consists of four main components such as the PMSM, the inverter, the main control unit and the position sensor.

Interconnections of the components are shown in Figure 3.7

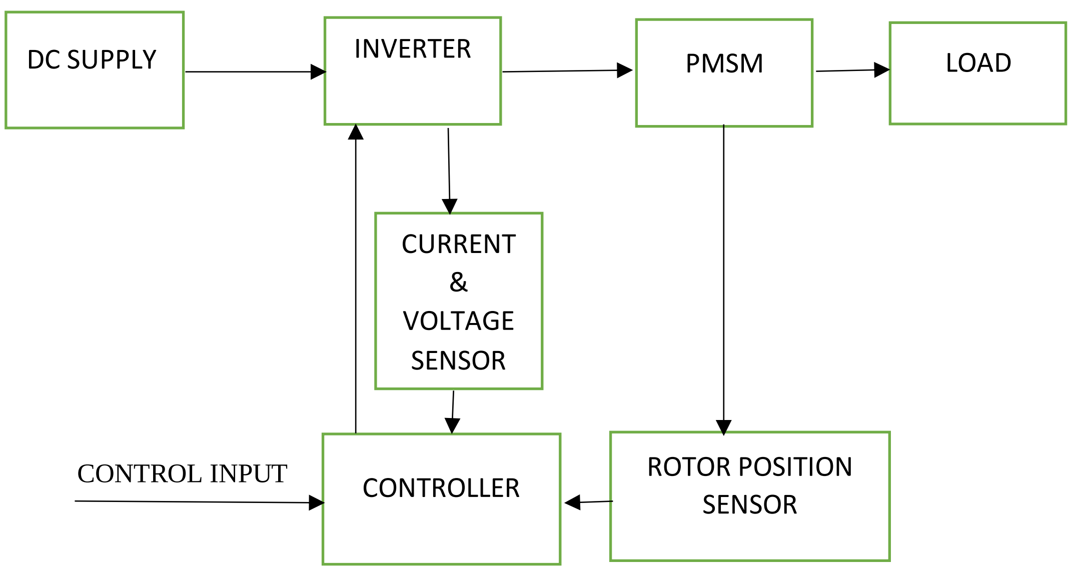


Figure 3.7 Components Permanent Magnet Synchronous Motor Drive

3.6. Equivalent Circuit of PMSM

Equivalent circuit is essential for the proper simulation and designing of the motor. It is achieved and derived from the d-q modelling of the motor using the voltage equations of the stator. From the assumption, rotor d axis flux is represented by a constant current source which is described through the following equation,

$$\lambda_f = L_{dm} i_f \tag{2.14}$$

Where, λ_f -Field Flux Linkage

L_{dm} -d-axis Magnetizing Inductance

i_f -Equivalent Permanent Magnet Field Current.

The Figure 2.8 shows the equivalent circuit of PMSM without damper windings.

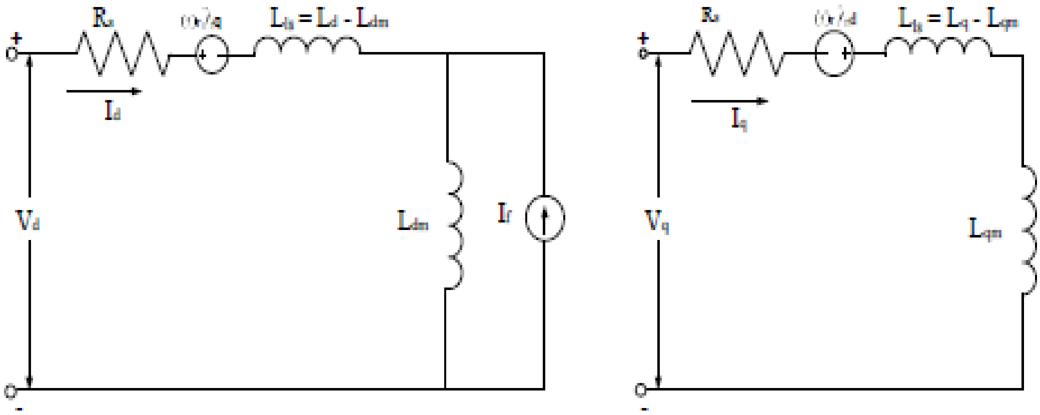


Figure 3.8 Equivalent Circuit of PMSM without Damper Windings

3.7 Steady-State Torque Versus Speed Characteristics

The relationship between steady-state torque and speed in Permanent Magnet Synchronous Motors (PMSMs) is critical for evaluating the motor's performance and suitability in various applications. This characteristic curve provides insights into the motor's behaviour under different load conditions, defining its operating limits and efficiency.

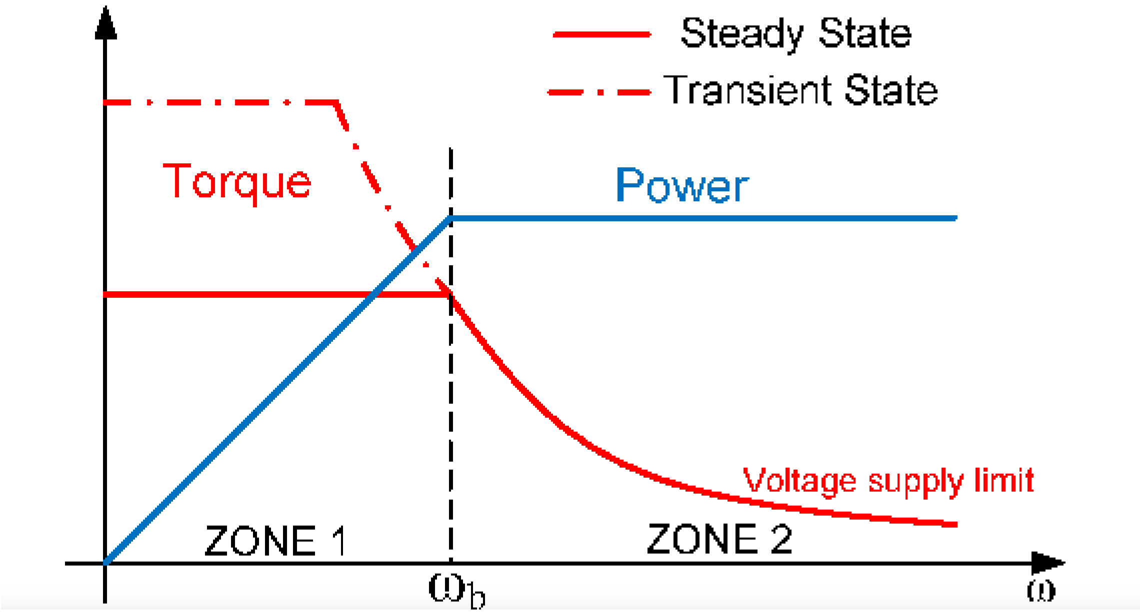


Figure 3.9 Steady State Torque Versus Speed

In the **Constant Torque Region**, the PMSM provides steady torque up to a base speed, ideal for applications like electric vehicles that need high torque at low speeds. Here, strategies like Field-Oriented Control (FOC) maximize torque per ampere.

In the **Constant Power Region**, beyond the base speed, torque decreases inversely with speed to maintain power output through field weakening, suitable for high-speed applications like fans and milling machines.

The **Field Weakening Region** allows further speed increase with reduced torque, as the stator voltage is maximized and flux is actively controlled to prevent saturation, useful for occasional high-speed bursts with low torque needs.

In **Breakdown and Stalling**, if load torque is too high at low speeds, stalling may occur; similarly, torque can drop sharply at high speeds near the breakdown point, emphasizing the need for robust torque control strategies.

3.8 Control Techniques of PMSM

Many techniques based on both motor designs and control techniques that have been proposed in literature to diminish the torque ripples in the PMSM.
And is shown in Figure 3.10**.**

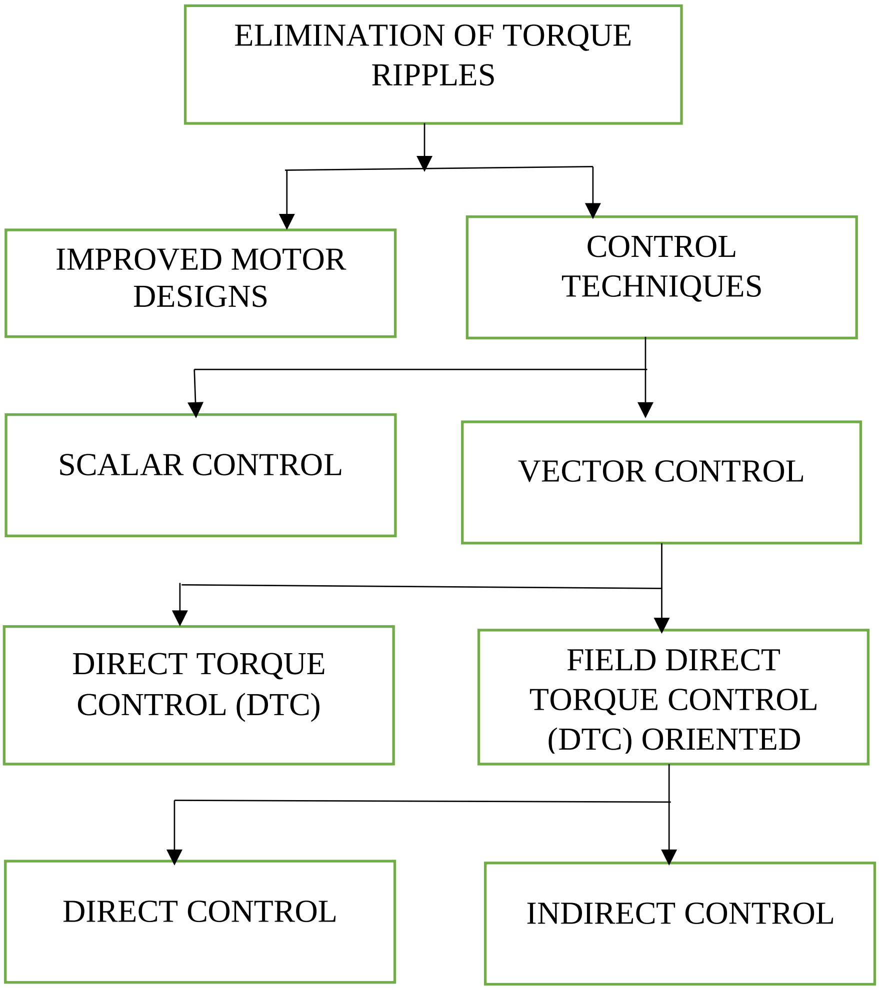


Figure 3.10 Classification of the Various Control Techniques

3.8.1 Closed Loop Control Of PMSM

Both Direct Torque Control (DTC) and Field-Oriented Control (FOC) are advanced control strategies primarily used for controlling Permanent Magnet Synchronous Motors (PMSMs) and, by extension, the inverters that drive these motors. Here's how they relate to PMSM and inverter control:

Field-Oriented Control (FOC)

Purpose: FOC is used to control the torque and magnetic flux of PMSMs independently. It provides precise control over motor performance by aligning the motor current with the rotor's magnetic field.

Operation:

- It utilizes transformations (Clarke and Park transformations) to convert three-phase motor currents into a two-dimensional rotating reference frame (d-q axes).
- By controlling the d-axis (flux) and q-axis (torque) currents independently using controllers (like PI controllers), FOC enhances the dynamic response and efficiency of PMSMs.
- **Inverter Control**: In the context of inverters, FOC determines the switching states of the inverter to achieve the desired output voltage and current waveforms, optimizing the motor operation.

Direct Torque Control (DTC)

Purpose: DTC is designed to control the torque and flux of PMSMs directly, offering rapid torque response and high performance.

Operation:

- DTC measures the actual torque and flux in real-time and compares them with reference values. Based on this comparison, it directly adjusts the inverter switching states to regulate torque and flux without the need for a separate current controller.
- This results in a faster response time and reduced torque ripple compared to traditional control methods.
- **Inverter Control**: DTC operates by directly influencing the inverter's switching states, allowing for precise control of the motor torque and flux, leading to improved performance characteristics.

CHAPTER-4

CONVENTIONAL SIX SWITCH INVERTER BASED 3ϕ PMSM MOTOR DRIVES

4.1 Design and Implementation of a Six-Switch Inverter for Three-Phase PMSM Motor Drives

The six-switch inverter, also known as a three-phase full-bridge inverter, is a fundamental component in the field of power electronics, particularly for applications involving three-phase motor drives such as Permanent Magnet Synchronous Motors (PMSMs). This section outlines the design, operation, and performance considerations of six-switch inverters for driving PMSM systems.

The Figure 4.1 shows the three phase six switch VSI fed PMSM drive.

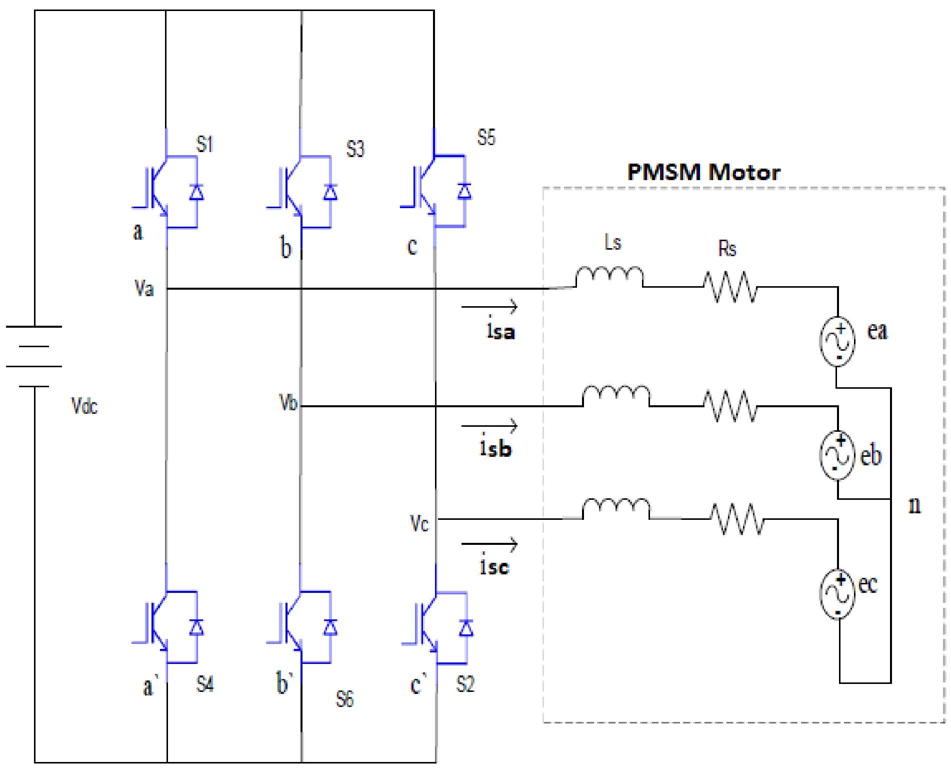


Figure 4.1 Three Phase Voltage Source Inverter fed PMSM drive

4.1.1.Different modes of operation:

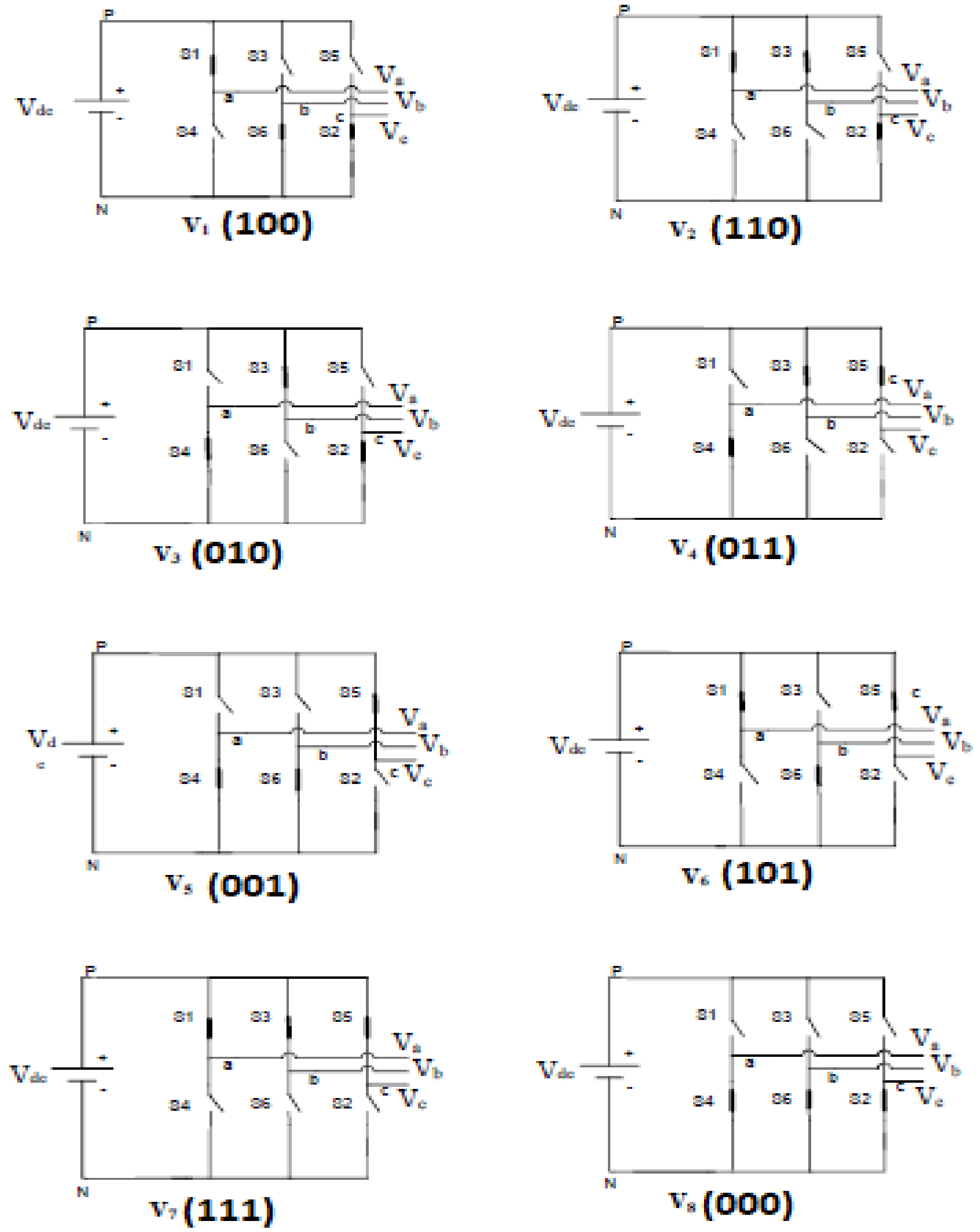


Figure 4.2 Eight Switching State Topologies of a Voltage Source Inverter

Representation of Three-Phase Quantities

In a three-phase system, the output voltages V_a, V_b and V_c are sinusoidal and phase-shifted by 120 degrees relative to each other. To simplify the analysis and control of these voltages, they can be transformed into a space vector in a complex plane using the following transformation:

$$V_S = \frac{2}{3}(V_a + V_b * e^{j\frac{2\pi}{3}} + V_c * e^{j\frac{4\pi}{3}}) \quad (4.1)$$

Where,

V_S is the resultant space vector,

$e^{j\frac{2\pi}{3}}$ and $e^{j\frac{4\pi}{3}}$ are complex operators representing the 120-degree phase shifts.

This transformation maps the three-phase quantities into a rotating vector in the complex plane, known as the space vector.

- The pole voltage of one phase of the converter has two switching states: 1 ($=V_{dc}$) and 0(=0).
- The converter has total eight switching states (2*2*2=8). These are: (000,111,100,110,010,011,001,101).
- There are six active vectors (100,110,010,011,001,101) and two zero vectors (000,111).

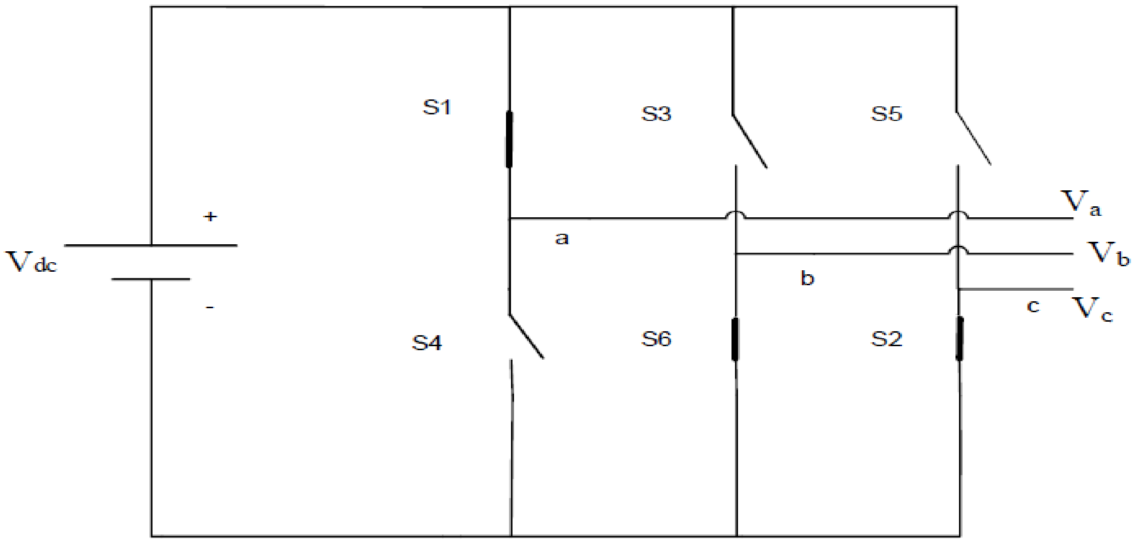


Figure 4.3 Topology 1-V_1(100) of a Voltage Source Inverter

Space vector for 100 combination

- $V_{AO}(t) = V_{dc}, V_{BO}(t) = 0, V_{CO}(t) = 0$ (4.2)
- $V_{An}(t) = \frac{2}{3}V_{AO}(t) - \frac{1}{3}V_{BO}(t) - \frac{1}{3}V_{CO}(t) = \frac{2}{3}V_{dc}$ (4.3)
- $V_{Bn}(t) = \frac{2}{3}V_{BO}(t) - \frac{1}{3}V_{CO}(t) - \frac{1}{3}V_{AO}(t) = -\frac{1}{3}V_{dc}$ (4.4)
- $V_{Cn}(t) = \frac{2}{3}V_{CO}(t) - \frac{1}{3}V_{AO}(t) - \frac{1}{3}V_{BO}(t) = -\frac{1}{3}V_{dc}$ (4.5)
- $V_R(t) = \frac{2}{3}\left[V_{An}(t) + V_{Bn}(t) * e^{j\frac{2\pi}{3}} + V_{Cn}(t) * e^{j\frac{4\pi}{3}}\right] = \frac{2}{3}V_{dc}e^{j0}$ (4.6)

Space Vector	Switching State	Resultant Space vector	
V_0	**000**	$\overline{V_0} = 0$	**Zero Vector**
V_1	**100**	$\overline{V_1} = \frac{2}{3}V_{dc}e^{j0}$	**Active Vector**
V_2	**110**	$\overline{V_2} = \frac{2}{3}V_{dc}e^{j\frac{\pi}{3}}$	
V_3	**010**	$\overline{V_3} = \frac{2}{3}V_{dc}e^{j\frac{2\pi}{3}}$	
V_4	**011**	$\overline{V_4} = \frac{2}{3}V_{dc}e^{j\frac{3\pi}{3}}$	
V_5	**001**	$\overline{V_5} = \frac{2}{3}V_{dc}e^{j\frac{4\pi}{3}}$	
V_6	**101**	$\overline{V_6} = \frac{2}{3}V_{dc}e^{j\frac{5\pi}{3}}$	
V_7	**111**	$\overline{V_7} = 0$	**Zero Vector**

Table 4.4 Space Vector, Switching State, Resultant Voltage Vector

4.2 Principle of SVPWM

- Space vector PWM is an extension of sine triangle PWM. Here the PWM is done by using space vectors.
- The space vectors are switched for certain duration of time in a cycle so as to produce the resultant vector.
- To generate V_{Ref}, SVPWM employs the two adjacent active vectors and a combination of zero vectors. Mathematically, this can be expressed as:

$$V_{ref} = V_1T_1 + V_2T_2 + V_0T_0 \quad (4.7)$$

Where:

- V_1 and V_2 are the adjacent active vectors in the sector containing V_{ref},
- T_1 and T_2 are the durations for which V_1 and V_2 are applied,
- T_0 is the time for applying the zero vectors,
- T_S is the total switching period.
- In space vector PWM, $T_{01} = T_{07} = T_0 / 2$.

The duration T_1, T_2 and T_0 are calculated based on the position and magnitude of to ensure that the average output voltage over T_S matches V_{ref}.

4.2.1. Representation of space vectors

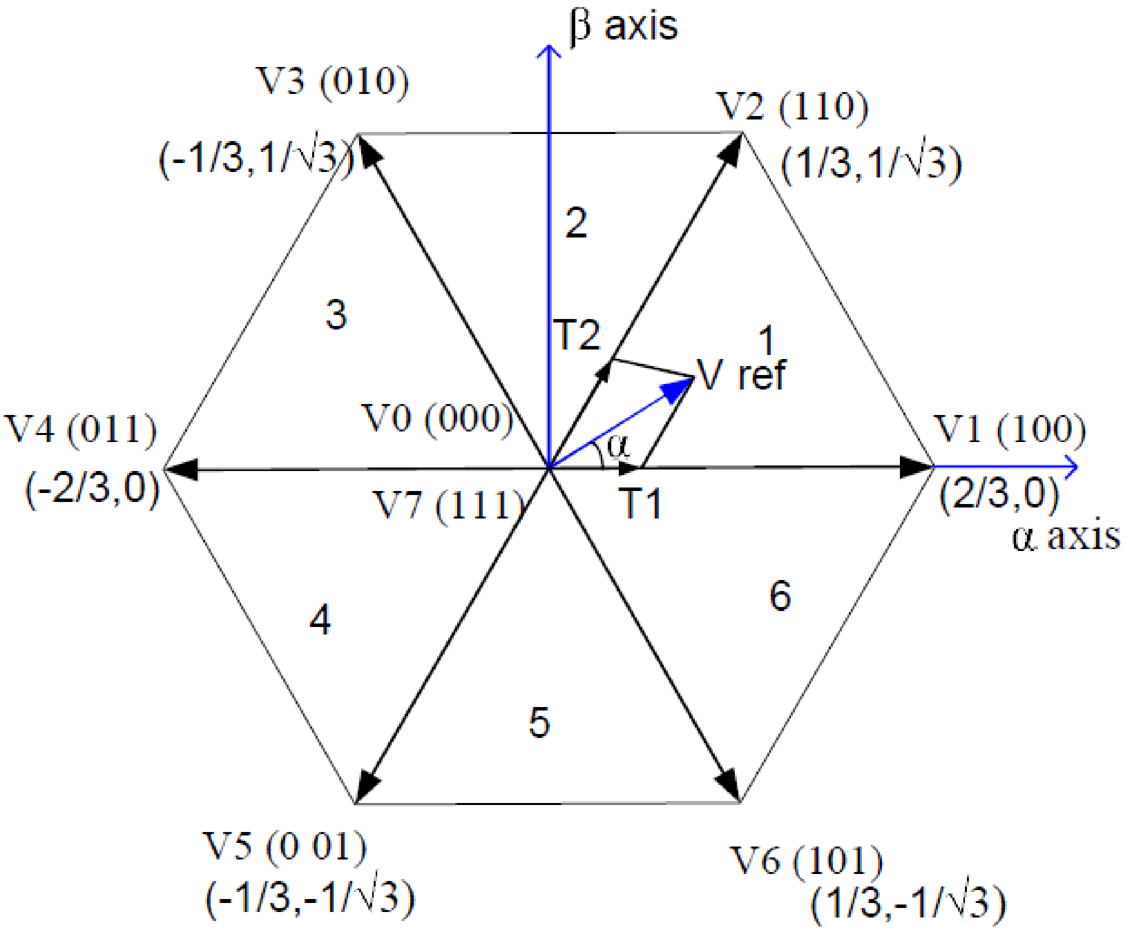


Figure 4.5 Basic Switching Vectors and Sectors

4.2.2 Determination of Switching Times for Sector 1

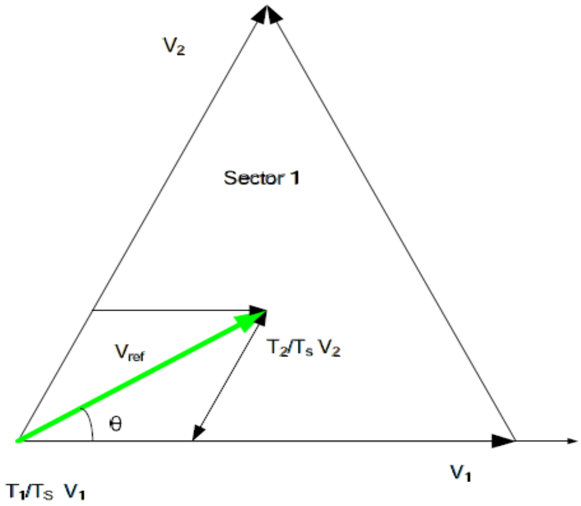


Figure 4.6 Determination of Switching Times for Sector 1

The time durations T1, T2 and T0 are solved by and can be arranged as follows,

$$T_1 = T_S m \frac{\sin\left(\frac{\pi}{3} - \theta\right)}{\sin\left(\frac{\pi}{3}\right)} \tag{4.8}$$

$$T_2 = T_S m \frac{\sin(\theta)}{\sin\left(\frac{\pi}{3}\right)} \tag{4.9}$$

$$T_0 = T_7 = T_S - (T_1 + T_2) \tag{4.10}$$

Where, m= $\frac{|V_{ref}|}{2V_{dc}/3}$ is modulation index, $(0 \le \theta < 60)$

For the sectors 2-6 the same rules apply. A voltage reference vector V_{ref} can be approximated by two adjacent switching space vectors and two zero vectors using PWM technique. It is necessary to arrange the switching sequence so that the switching frequency of each inverter leg can be minimized.

Figure 3.26 shows the switching sequence to minimize the ripple content of output current. The three-phase inverter legs are switched at the beginning from the zero state, at the ending of the other zero state during the sampling time T_S. This rule applies normally to the three phase inverters as the switching sequence for example "$V_0 - V_1 - V_2 - V_7 - V_7 - V_2 - V_1 - V_0$" in sector-1 , Therefore, the switching cycle of the output voltage is double the sampling time, and the two output voltage waveforms become symmetrical during 2TS.

4.2.3. Representation of switching sequence of individual sectors

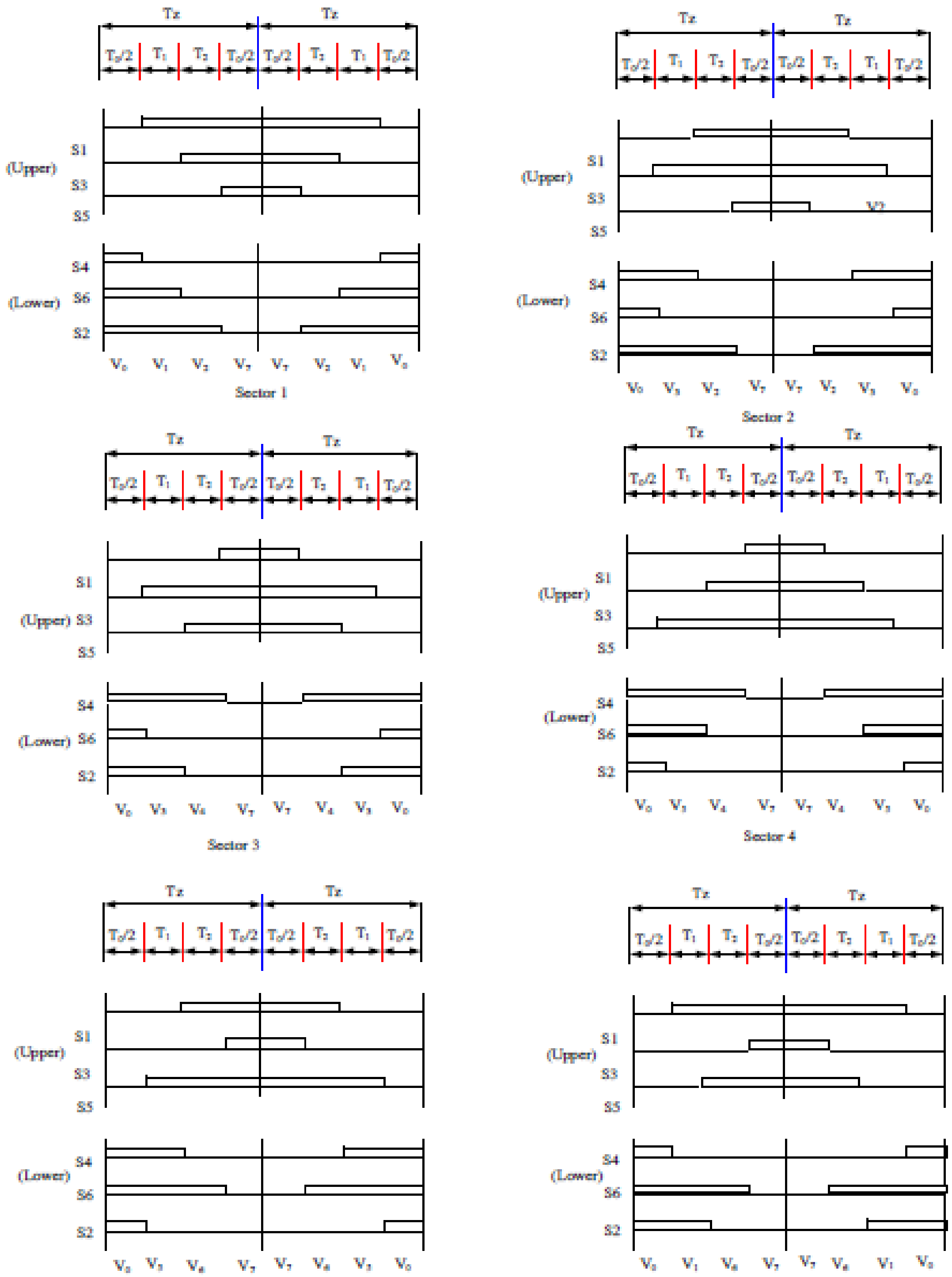


Figure 4.7 SVPWM Switching Patterns at Each Sector

4.3 Locus Comparisons of SVPWM with SPWM

Sine PWM (Sinusoidal Pulse Width Modulation) and SVPWM (Space Vector Pulse Width Modulation) are both modulation techniques used for controlling the output voltage and frequency in inverter-driven motor applications. Here's a comparison of the two methods:

- The maximum output voltage based on SVPWM (Space Vector Pulse Width Modulation) theory is $(2/\sqrt{3})$ times as large as the conventional SPWM (Sinusoidal Pulse Width Modulation).

- In conventional SPWM, locus of the reference vector is the inside of a circle with a radius of $(1/2)V_{dc}$. In the SVPWM it can be shown that the length of each of the six vectors is $(2/3)V_{dc}$.

- SVPWM generates less harmonic distortion in the output voltage or currents than SPWM.

- SVPWM provides more efficient use of supply voltage than SPWM.

- Voltage Utilization of SVPWM = (2/ 3) times of SPWM.

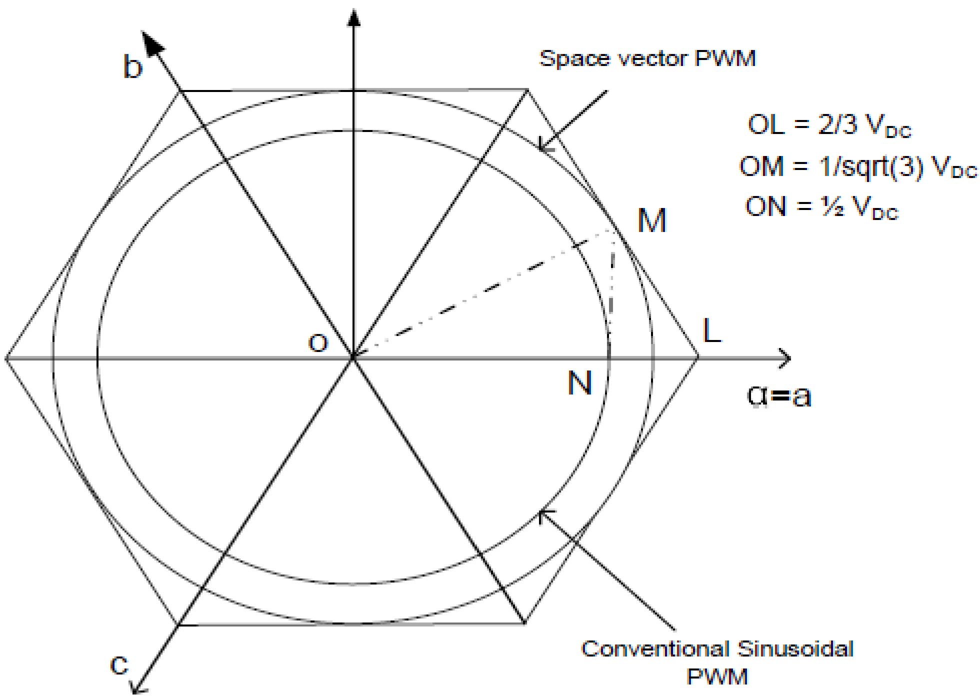


Figure 4.8 Locus Comparisons of SVPWM with SPWM

CHAPTER-5

FOUR SWITCH INVERTER BASED 3ϕ PMSM MOTOR DRIVES

5.1 Design and Implementation of a Four-Switch Inverter for Three-Phase PMSM Motor Drives

The design and implementation of a four-switch inverter for three phase Permanent Magnet Synchronous Motor (PMSM) drives involves a streamlined approach compared to conventional six-switch inverters. This topology is beneficial for cost reduction, simplified control schemes, and compact hardware structures.

The Figure 5.1 shows the three phase Four-switch VSI fed PMSM drive.

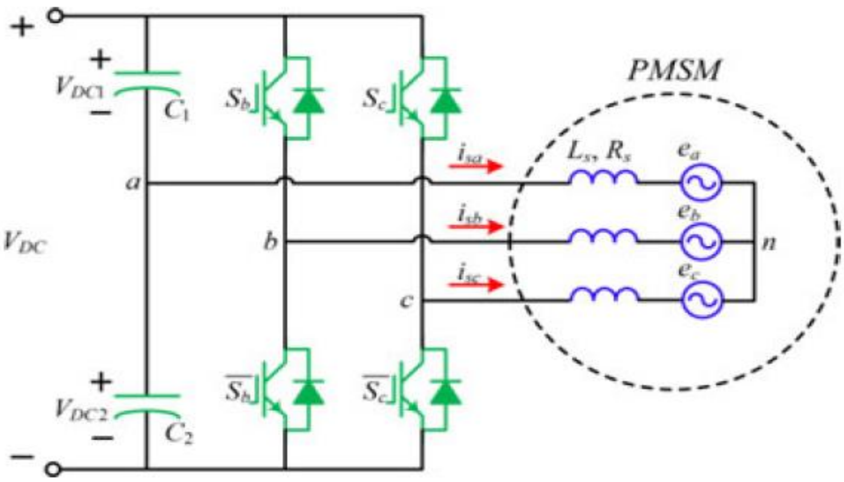


Figure 5.1 Three Phase Four-Switch Voltage Source Inverter fed PMSM Drive.

5.2 Four-Switch Three-Phase Inverter (FSTPI) – Construction and Working

A **Four-Switch Three-Phase Inverter (FSTPI)** is constructed to deliver three-phase AC output using only four semiconductor switches. Below are the constructional elements and their roles in the system:

1. **Switching Devices (IGBTs/MOSFETs)**
    - **Four Main Switches**: The inverter consists of four power switches (e.g., IGBTs or MOSFETs) arranged into two legs:
    - **Leg 1**: Contains switches S_b and $\overline{S_b}$.
    - **Leg 2**: Contains switches S_c and $\overline{S_c}$.
    - Each switch is paired with a freewheeling diode to provide a path for reactive current when the switch is off, ensuring safe operation and minimizing voltage spikes.
2. **DC Power Supply**
    - The input to the inverter is provided by a DC power source, such as a battery or rectified AC supply. The positive and negative terminals of this supply are connected to the two inverter legs.
3. **Connections to the Motor**
    - **Phase Connections**: The three-phase Permanent Magnet Synchronous Motor (PMSM) is connected as follows:
    - The outputs of the two legs (b, c) connect to two of the motor's three windings.
    - The third motor winding connects to the midpoint of the DC link capacitor (a), which acts as a common reference point.
4. **Gate Driver Circuit**
    - **Gate Driver ICs**: These circuits are essential for providing the appropriate gate-to-source voltage required to turn the power switches on and off efficiently. They must include isolation and protection features such as dead-time insertion and short-circuit protection to ensure safe operation.
    - **Control Signals**: Gate drivers are controlled by signals generated from a microcontroller or DSP, which executes the modulation algorithm (e.g., SVPWM).
5. **Microcontroller/Digital Signal Processor (DSP)**
    - **Control Unit**: A microcontroller or DSP runs the algorithm for switching control. This unit generates the necessary PWM signals to drive the switches in a precise sequence to create the desired AC output.
    - **Feedback Mechanism**: The control unit often includes feedback from motor sensors (e.g., current sensors or encoders) to regulate motor performance and adjust switching to optimize torque and speed.

4.2 FSTPI Inverter's Different Modes of Operation

Mode 1

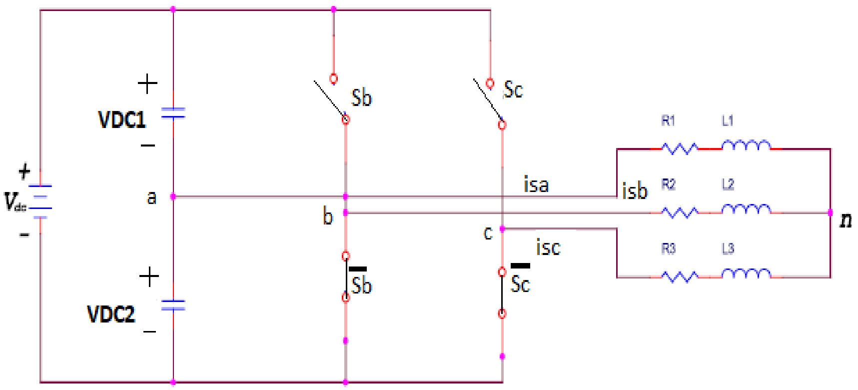


Figure 5.2 Mode of operation when $S_b = 0$, $S_c = 0$.

Mode 2

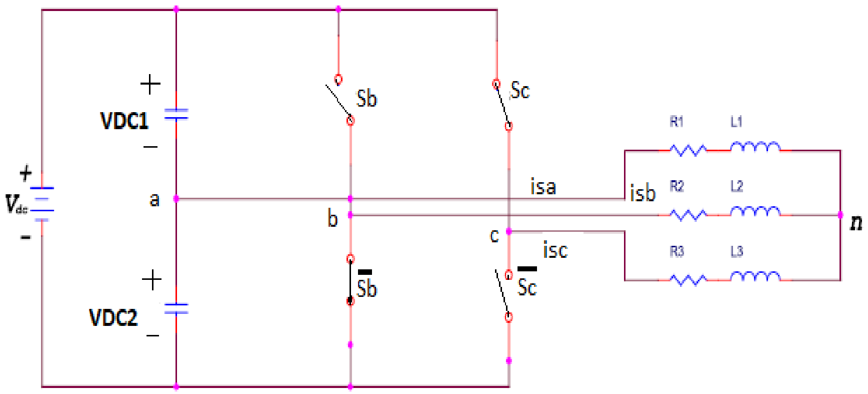


Figure 5.3 Mode of operation when $S_b = 0$, $S_c = 1$.

Mode 3

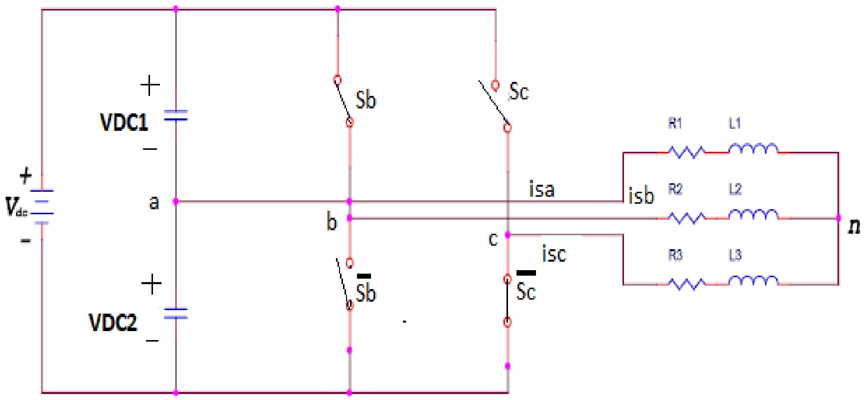


Figure 5.4 Mode of operation when $S_b = 1$, $S_c = 0$.

Mode 4

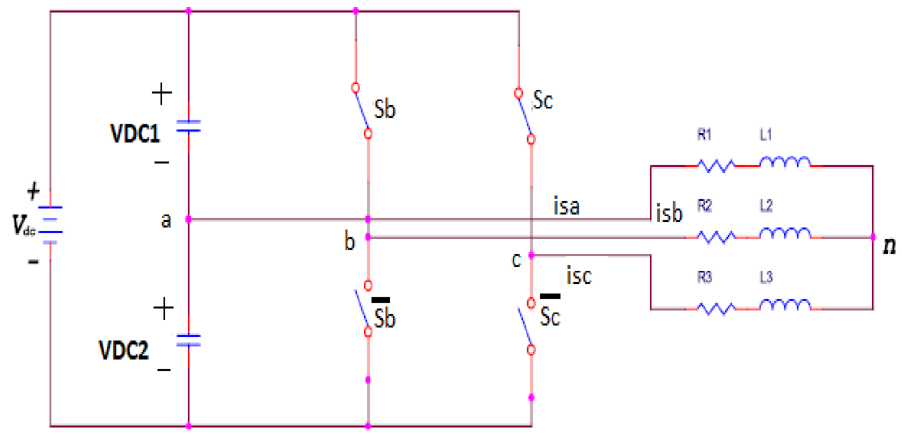


Figure 5.5 Mode of operation when S_b = 1 , S_c = 1.

The key feature of the TPFS inverter-fed PMSM drive is its unique set of stator voltage vectors, which is completely different from that of a TPSS inverter. The stator voltage of the TPFS inverter-fed PMSM drive is given by

$$V_S = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{V_{DC1}}{6}\begin{bmatrix} -p_b - p_c - 2 \\ 2p_b - p_c + 1 \\ -p_b + 2p_c + 1 \end{bmatrix} + \frac{V_{DC2}}{6}\begin{bmatrix} -p_b - p_c + 2 \\ 2p_b - p_c - 1 \\ -p_b + 2p_c - 1 \end{bmatrix} \quad (5.1)$$

Where, p_b and p_c are switching functions defined as,

$$p_j = \begin{Bmatrix} 1, S_j, closed \\ -1, \overline{S_j}, closed \end{Bmatrix}, \text{ j= b, c} \quad (5.2)$$

Representing the switching states of the four switches, Performing Clark's transformation and setting all possible combinations of the switching state to (5.1), the four basic vectors of the stator voltage in the $\alpha\beta$ coordinate system are given in Table I.

As seen from Table I, the zero vector, which fills in the remaining time portions aside from the active vectors in the SVM schemes, is absent in the TPFS inverters. Therefore, the equivalent zero vectors are synthesized using a pair of opposite vectors, therein producing additional complexity of the modulation strategies.

Moreover, because the stator current i_{sa} flows directly into the neutral point of the dc bank, the node current equation of the neutral point can be expressed as,

$$C\frac{dV_{DC1}}{dt} - C\frac{dV_{DC2}}{dt} = i_{sa} \tag{5.3}$$

It is assumed that $i_{sa} = |i_S|\cos\left(\omega_r t + \pi/2\right)$, by integrating both sides of (5.3), the capacitor voltages at steady state are given by ,

$$V_{DC1} - V_{DC2} = \frac{|i_S|}{\omega_r C}\cos(\omega_r t) \tag{5.4}$$

From (5.4), it is concluded that the capacitor voltages V_{DC1} and V_{DC2} are not constant in the TPFS inverter-fed PMSM drive; rather, they exhibit periodical fluctuations. Consequently, vectors of the TPFS inverter-fed PMSM drive are not symmetrical as in the TPSS inverters, which results in another challenge to the modulation strategy.

TABLE I
BASIC SPACE VECTORS OF THE TPFS INVERTER-FED PMSM DRIVE

Switching state (p_b, p_c)	$\overline{V}_\alpha$	$j\overline{V}_\beta$
$\overline{V}_1(0,0)$	$\frac{2V_{DC2}}{3}$	j0
$\overline{V}_2(1,0)$	$\frac{(V_{DC2} - V_{DC1})}{3}$	$j\frac{(V_{DC1} + V_{DC2})}{\sqrt{3}}$
$\overline{V}_3(1,1)$	$\frac{-2V_{DC1}}{3}$	j0
$\overline{V}_4(0,1)$	$\frac{(V_{DC2} - V_{DC1})}{3}$	$-j\frac{(V_{DC1} + V_{DC2})}{\sqrt{3}}$

4.3 Space Vector Representation of Four-Switch Three-Phase Inverter

The space vector representation of a three-phase four-switch inverter (FSTPI) offers a compact and insightful way to analyse and control the inverter's behaviour. Unlike the traditional six-switch three-phase inverter, the four-switch topology reduces the number of switching devices, lowering costs and simplifying the circuit design. However, this simplification imposes constraints on the achievable voltage vectors and modulation strategies.

The Figure 5.6 shows the Four Basic Active Vector Produces by three phase Four-switch VSI fed PMSM drive.

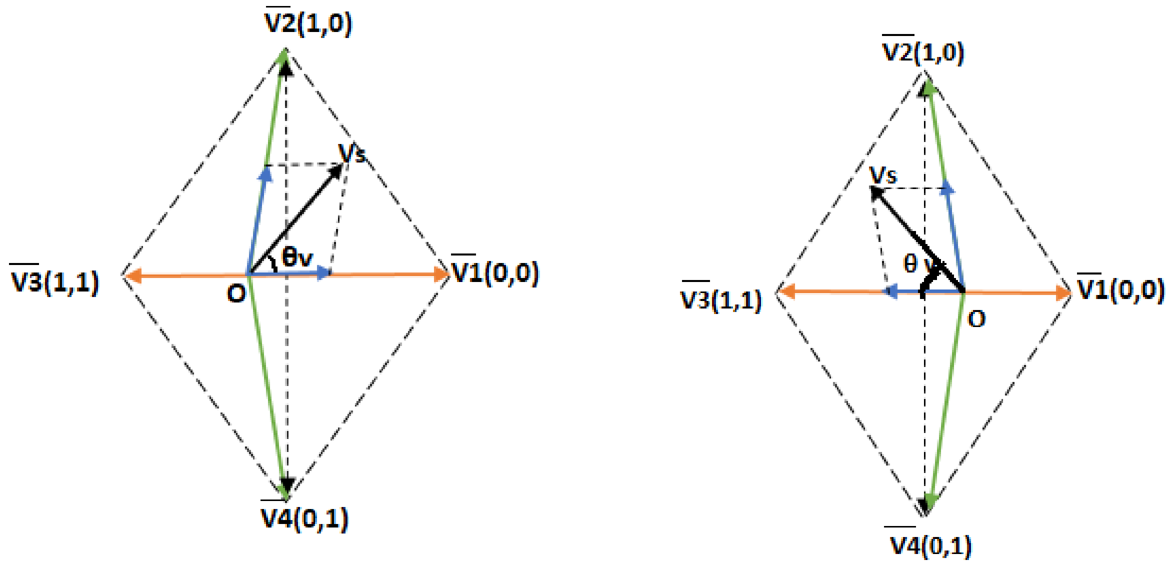


Fig.5.6. Voltage space vectors in the plane-$\alpha\beta$ (a) in case of $V_{DC2} \succ V_{DC1.}$,(b) in case of $V_{DC1} \succ V_{DC2}$.

Combinations of switching S1-S4 result in 4 general space vectors $\overline{V_1} \rightarrow \overline{V_4}$ in (TABLE 1).
Voltage imbalance in the DC link causes the space vector origin to shift along the $\overline{V_1}$ to $\overline{V_3}$ axis, with $\overline{V_1}$ & $\overline{V_3}$ no longer being equal in magnitude, as described in Table 1.

4.4 SVM(Space Vector Modulation) OF THE TPFS INVERTER

The main concept of the SVM in a TPFS inverter is similar to that of a six switch inverter, where the reference voltage vector should be synthesized by two active basic vectors according to the principle of the voltage–second value being equal. However, the core problem of the modulation in a TPFS inverter is the synthesis of the equivalent zero vector, which is directly related to the performance of the modulation strategy. Generally, two opposite vectors (either $V_1 - V_3$ or $V_2 - V_4$), whose voltage– second integral is equal to zero, can be utilized to synthesize the zero vectors.

For example, when the reference stator voltage vector V_S lies in Sector I, the effective part is always synthesized by V_1 and V_2 , whereas the remaining part can be synthesized by either $V_1 - V_3$ or $V_2 - V_4$, as shown in Fig. 3. In SVM1 method shown in Fig. 5.7(a), the equivalent zero vectors are synthesized by $V_1 - V_3$; thus, the reference vector V_S is synthesized by V_1 , V_2 and V_3 .

Alternatively, in the SVM2 method shown in Fig. 5.7(b), the equivalent zero vectors are synthesized by $V_2 - V_4$; thus, V_S is synthesized by V_1 , V_2 and V_4. Note that the capacitor voltages are assumed to be identical ($V_{DC1} = V_{DC2} = V_{DC}/2$) to simplify the analysis. Based on the zero vector synthesis approaches, two kinds of SVM strategy are provided, yielding two switching sequences as follows:

SVM1: $V_1 - V_2 - V_3 - V_2 - V_1$, SVM2: $V_2 - V_1 - V_4 - V_1 - V_2$.

TABLE II
VECTORS UTILIZED IN THE TWO SVM SCHEMES

SVM	Sector I	Sector II	Sector III	Sector IV
SVM1	$V_1, V_2 \& V_3$	$V_1, V_2 \& V_3$	$V_1, V_3 \& V_4$	$V_1, V_3 \& V_4$
SVM2	$V_1, V_2 \& V_4$	$V_2, V_3 \& V_4$	$V_2, V_3 \& V_4$	$V_1, V_2 \& V_4$

As a result, three out of four basic vectors should be adopted for the synthesis. When the reference voltage vector lies in other sectors, the three utilized vectors in the two SVM schemes are listed in Table II.

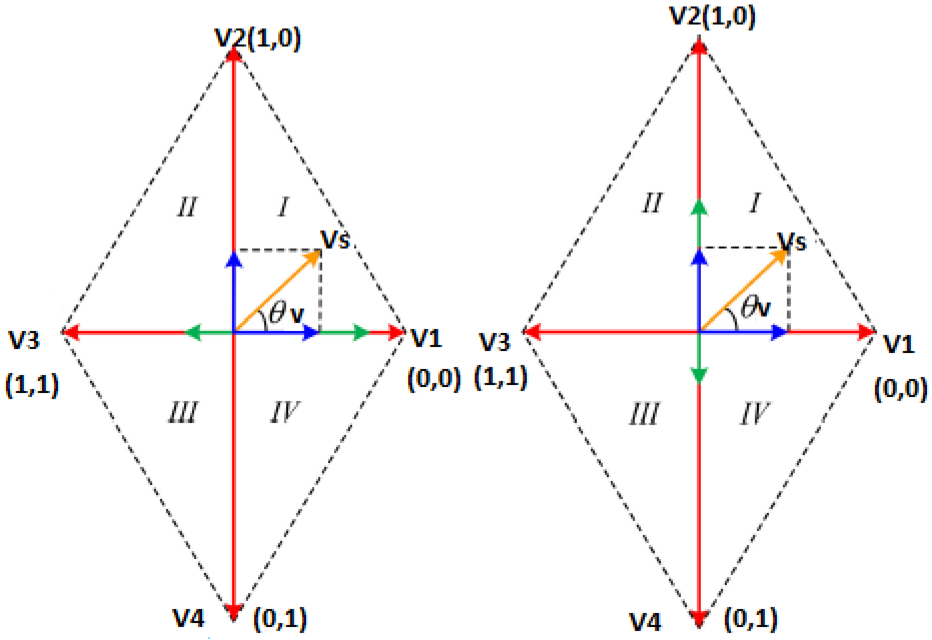


Fig.5.7. Space vector synthesis in TPFS inverter-fed PMSM drives: (a) using $V_1 - V_3$ to synthesize zero vectors (SVM1) and (b) using $V_2 - V_4$ to synthesize zero vectors (SVM2).

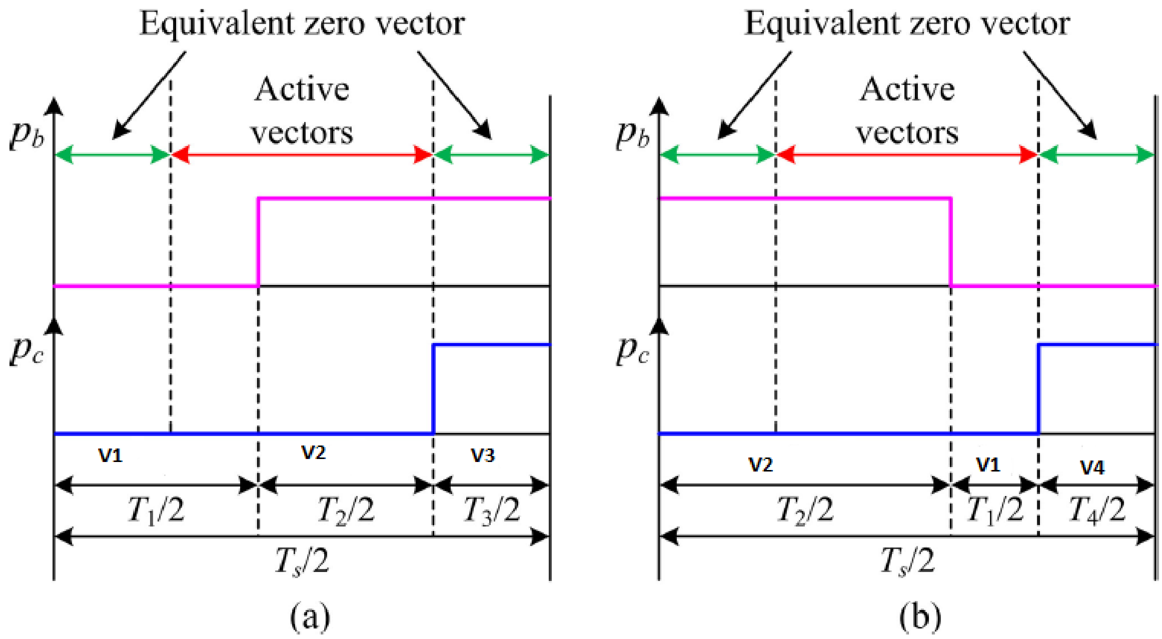


Fig.5.8. Switching sequences of TPFS inverter-fed PMSM drives: (a) SVM1 and (b) SVM2.

Once the utilized vectors are determined, their duration times per switching period can be calculated by,

$$V_1T_1 + V_2T_2 + V_3T_3 + V_4T_4 = V_ST_S \quad (5.5)$$

$$T_1 + T_2 + T_3 + T_4 = T_S \quad (5.6)$$

One of the vector duration times is equal to zero because only three vectors are utilized per switching period. For example, T_4 is equal to zero when utilizing SVM1 in Sectors I and II; T_1 is equal to zero when utilizing SVM2 in Sectors II and III.

According to (5.5) and (5.6), the switching sequences of SVM1 and SVM2 are shown in Fig. 5.8. Considering the symmetry of the switching patterns, only half of the switching period is presented. The active parts of the space vectors in both SVM schemes are the same, i.e., V_1 and V_2.

CHAPTER-6

FOUR-SWITCH THREE PHASE INVERTER BASED PMSM MOTOR DRIVES

6.1. THEORY BEHIND FSTPI BASED PMSM MOTOR DRIVE

Structure of Four Switch Three Phase Inverter The circuit of FSTPI is shown in Fig. 1.

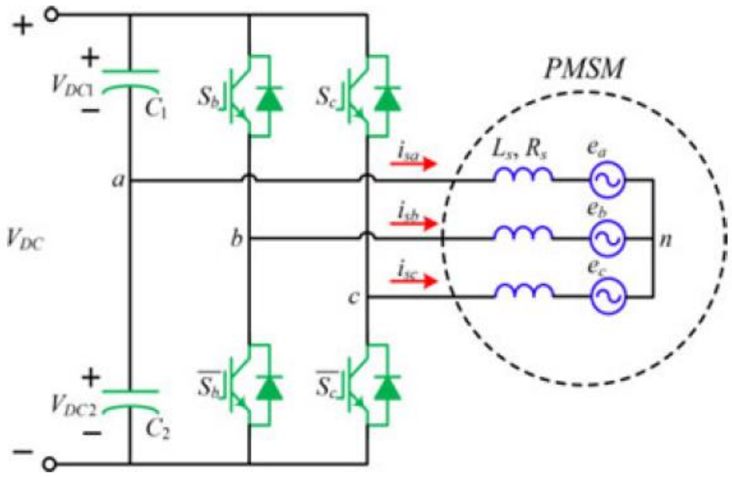


Fig.6.1. Structure of Four Switch Three Phase Inverter Circuit.

FSTPI consists of four switches, b and c nodes are connected to the phase B and C phases of the PMSM motor respectively. The A phase of the motor is connected to the centre potential of the DC link split capacitor.

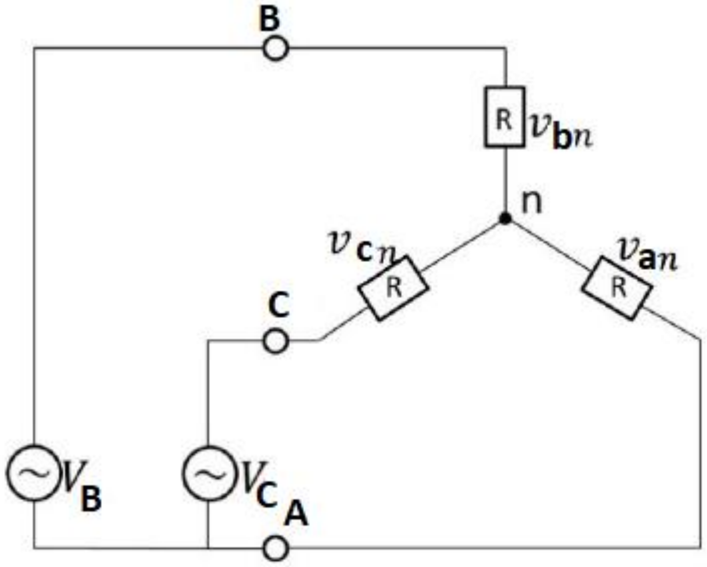


Fig.6.2. The V connection of a three phase circuit is shown.

$$V_B = V_m \sin(\omega t) \quad (6.1)$$

$$V_C = V_m \sin(\omega t + \frac{\pi}{3}) \quad (6.2)$$

$$V_{an} = \frac{V_m}{\sqrt{3}} \cos(\omega t - \frac{5\pi}{6}) \quad (6.3)$$

$$V_{bn} = \frac{V_m}{\sqrt{3}} \cos(\omega t - \frac{\pi}{6}) \quad (6.4)$$

$$V_{cn} = \frac{V_m}{\sqrt{3}} \cos(\omega t + \frac{\pi}{2}) \quad (6.5)$$

$$V_{ab} = V_m \cos(\omega t - \frac{4\pi}{6}) \quad (6.6)$$

$$V_{bc} = V_m \cos(\omega t) \quad (6.7)$$

$$V_{ca} = V_m \cos(\omega t + \frac{4\pi}{6}) \quad (6.8)$$

As presented in Equation (6.1) and (6.2), V_B and V_C represent the two-phase AC power source with a phase difference of $\frac{\pi}{3}$. When this two-phase power supply voltage (V_B and V_C) is applied to a three-phase load, it generates a balanced three phase voltage system, namely V_{an}, V_{bn} and V_{cn}, as shown in Equation (6.3),(6.4),(6.5). Consequently, it can be observed that a two-phase AC power supply with a $\frac{\pi}{3}$ phase shift can effectively drive a three-phase PMSM motor. This principle forms the foundation of the operational mechanism of the Four Switch Three-Phase Inverter (FSTPI) drive.

6.2. Open-Loop Control of FSTPI-Fed PMSM Motor

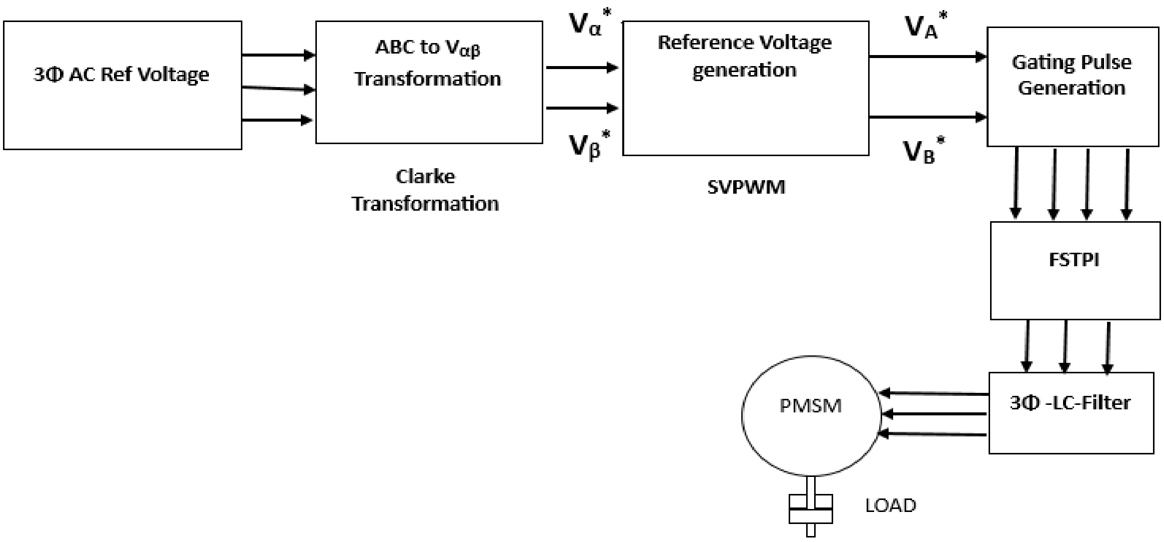


Fig.6.3. The block diagram for the open-loop control of a PMSM driven by a Four-Switch Three-Phase Inverter (FSTPI).

Figure 6.3 illustrates the block diagram for the open-loop control of a Permanent Magnet Synchronous Motor (PMSM) driven by a Four-Switch Three-Phase Inverter (FSTPI). In this configuration, the FSTPI converts the two-phase AC supply into a three-phase balanced output required to operate the PMSM. The control system operates in open-loop mode, where predefined switching signals are applied to the inverter switches without any feedback mechanism for speed or position correction. The open-loop control scheme relies on a space vector pulse width modulation (SVPWM) technique to minimize torque ripple while providing the required excitation for the motor. This configuration is suitable for applications where precise control is not essential, and the motor can run with a constant or predictable load.

6.3. Challenges in Four-Switch Open-Loop Control and the Role of Current Control Schemes

In four-switch open-loop control of FSTPI-fed PMSM drives, one major challenge is the fluctuation of DC-link capacitor voltages. These fluctuations can lead to imbalance in the output voltage, which subsequently affects the motor performance, causing variations in torque and speed. To mitigate this issue, current control schemes are introduced, as shown in Figure 6.4. By regulating the motor current, these schemes help stabilize the capacitor voltages, ensuring smoother motor operation and improved performance, especially under varying load conditions.

With the implementation of the current control technique, the fluctuations in DC link capacitor voltage are significantly reduced. This stabilization of capacitor voltage directly results in smoother motor operation, with reduced torque ripple and improved efficiency. Consequently, the current control approach enhances the reliability and performance of the FSTPI-fed PMSM drive, making it a viable solution for applications requiring stable and efficient motor control.

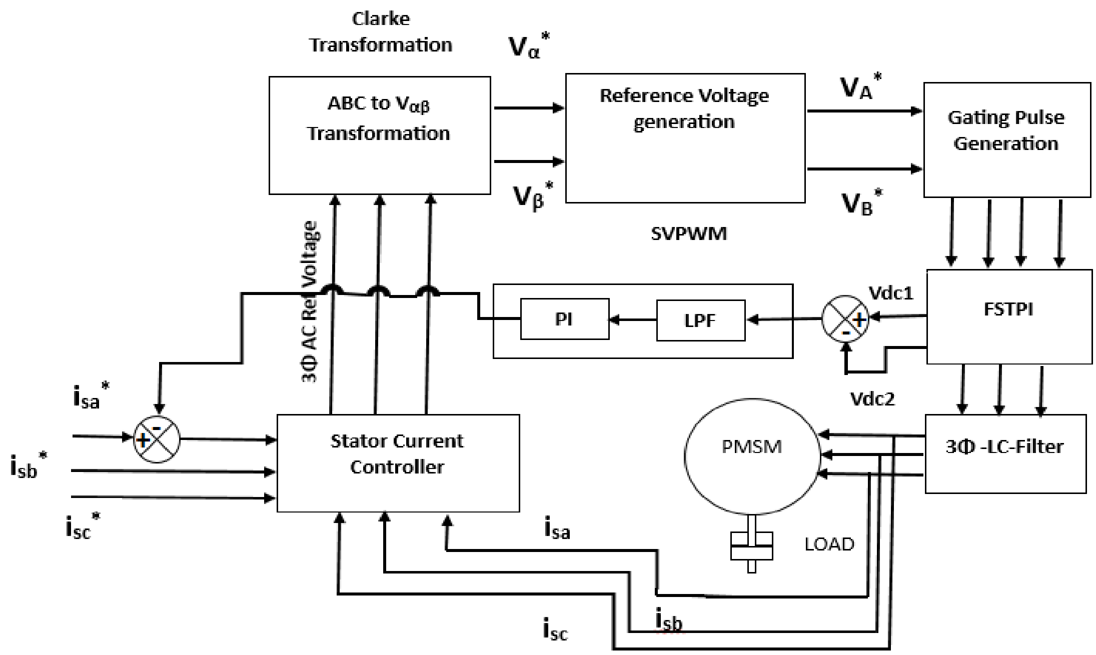


Fig.6.4. The block diagram of the current control scheme for the FSTPI-fed PMSM drive.

6.4. Field-Oriented Control (FOC) Based Space Vector Pulse Width Modulation (SVPWM) for Four-Switch Three-Phase Inverter (FSTPI) Fed Permanent Magnet Synchronous Motor (PMSM) Drive

Although the current control technique reduces capacitor voltage fluctuations, it operates as an open-loop system where the reference current is manually provided. This limitation can hinder the precision in controlling the PMSM drive's speed and torque under varying load conditions. To achieve enhanced control and dynamic performance, a closed-loop control technique is necessary. Therefore, a closed-loop control scheme for the four-switch inverter has been designed using Field-Oriented Control (FOC) with Space Vector Pulse Width Modulation (SVPWM). This approach enables precise regulation of both speed and torque by continuously adjusting the motor's current and voltage vectors in response to real-time feedback, thereby improving the stability and efficiency of the PMSM drive.

Following the implementation of Field-Oriented Control (FOC), a Space Vector Pulse Width Modulation (SVPWM) technique was employed to generate reference voltages for controlling the two active legs of the Four-Switch Three Phase Inverter (FSTPI). The primary goal of this approach is to create two reference voltage vectors that are phase-shifted by $\frac{\pi}{3}$ degrees, enabling efficient operation of the FSTPI in driving the PMSM. Using the SVPWM method, these two reference voltages were successfully generated, achieving the desired phase relationship.

Figure 6.5 represents the closed-loop control system for the FSTPI-fed PMSM drive.

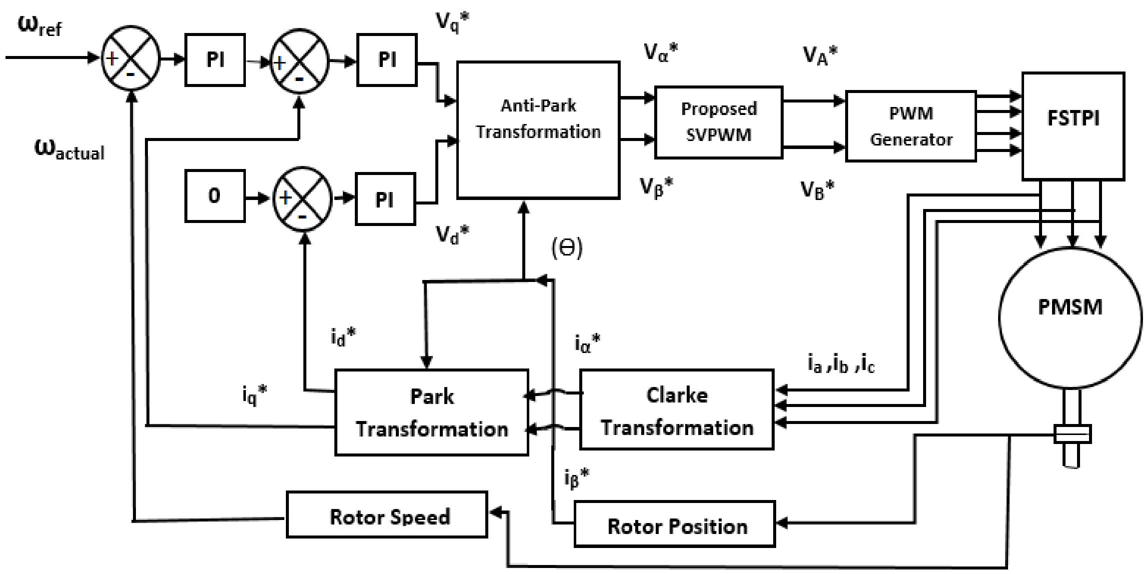


Fig.6.5. The block diagram of the Field-Oriented Control (FOC) based Space Vector Pulse Width Modulation (SVPWM) scheme applied to an FSTPI-fed PMSM drive

These reference signals are subsequently used to produce the switching pulses for the four switches within the inverter. By using the SVPWM-generated reference signals as inputs to the pulse generator, precise control over the inverter switching sequence is achieved. This control mechanism optimizes the inverter's voltage output, allowing for smoother and more stable operation of the PMSM. The use of phase-shifted reference voltages effectively minimizes torque ripple and enhances the overall performance and efficiency of the drive system under various operating conditions.

6.5. Conclusion of this Chapter

While the FOC-based SVPWM control scheme enhances the performance of the FSTPI-fed PMSM drive, inherent challenges remain due to the FSTPI topology. Specifically, one phase of the motor is directly connected to the midpoint of the DC split capacitor. Although increasing the capacitance value can provide some tolerance to stabilize the DC-link voltage and achieve a balanced three-phase stator current, this alone is not sufficient for maintaining consistent performance. The FOC and SVPWM control methods, though effective in regulating torque and speed, are inadequate on their own to fully address the voltage fluctuations in the DC capacitors associated with the FSTPI configuration.

To mitigate these issues, an additional control technique is required to actively compensate for the capacitor voltage fluctuations, ensuring stable and balanced three-phase current output. Therefore, in the next chapter, a current control technique is introduced as a solution. This current control approach effectively addresses the DC offset in the capacitor voltages of the FSTPI by integrating seamlessly with the existing FOC and SVPWM closed-loop control scheme. By employing this method, the proposed system achieves improved voltage stability, enabling the FSTPI-fed PMSM drive to operate efficiently with reduced torque ripple and enhanced reliability under various load conditions.

CHAPTER-7

7.1. Proposed FOC-based SVPWM of FSTPI-Fed PMSM Drive with Capacitor Voltage Offset Suppression

7.1.1. Introduction

As discussed in the previous chapter, the Four-Switch Three-Phase Inverter (FSTPI) topology presents several unique challenges when applied to Permanent Magnet Synchronous Motor (PMSM) drives. The primary issues associated with the FSTPI-fed PMSM drive are as follows

- **Phase Imbalance Due to Direct Connection to DC Split Capacitor Midpoint**: In the FSTPI configuration, one phase of the PMSM is directly connected to the midpoint of the DC split capacitor, which inherently lacks independent control over the current and voltage of this phase. This limitation in control leads to imbalance across the three-phase output, causing asymmetries in the stator current and voltage that degrade motor performance.
- **Capacitor Voltage Oscillations Under Load**: When driving a load, the DC-link capacitor voltages tend to oscillate, which disrupts the stability of the DC-link voltage. These fluctuations contribute to unbalanced output voltages, resulting in torque ripple that affects the smooth operation of the motor. The torque ripple not only impacts performance but may also lead to mechanical vibration and premature wear of motor components.
- **Complexity of the FOC and SVPWM Control Techniques**: Implementing Field-Oriented Control (FOC) in combination with Space Vector Pulse Width Modulation (SVPWM) for the FSTPI introduces additional complexity. While FOC with SVPWM is effective in achieving precise torque and speed control, integrating this approach with the unique topology of the FSTPI requires sophisticated control strategies to address both the phase imbalance and capacitor voltage fluctuations.

To address these challenges, this chapter presents a Field-Oriented Control (FOC) based Space Vector Pulse Width Modulation (SVPWM) approach specifically tailored for the unique requirements of the Four-Switch Three-Phase Inverter (FSTPI)-fed PMSM drive. This novel SVPWM technique is designed to provide effective management of the inverter's switching states, allowing precise control over the motor while accommodating the inherent limitations of the FSTPI topology. Additionally, a current control technique is proposed to mitigate the oscillations in the DC-link capacitor voltage. This current control approach actively compensates for fluctuations in one of the phase currents, ensuring a balanced three-phase output. Through the integration of these methods, the proposed control scheme effectively reduces torque ripple and enhances the overall stability and performance of the PMSM drive under various load conditions.

7.2. Block Diagram of Proposed FOC-based SVPWM of FSTPI-Fed PMSM Drive with Capacitor Voltage Offset Suppression

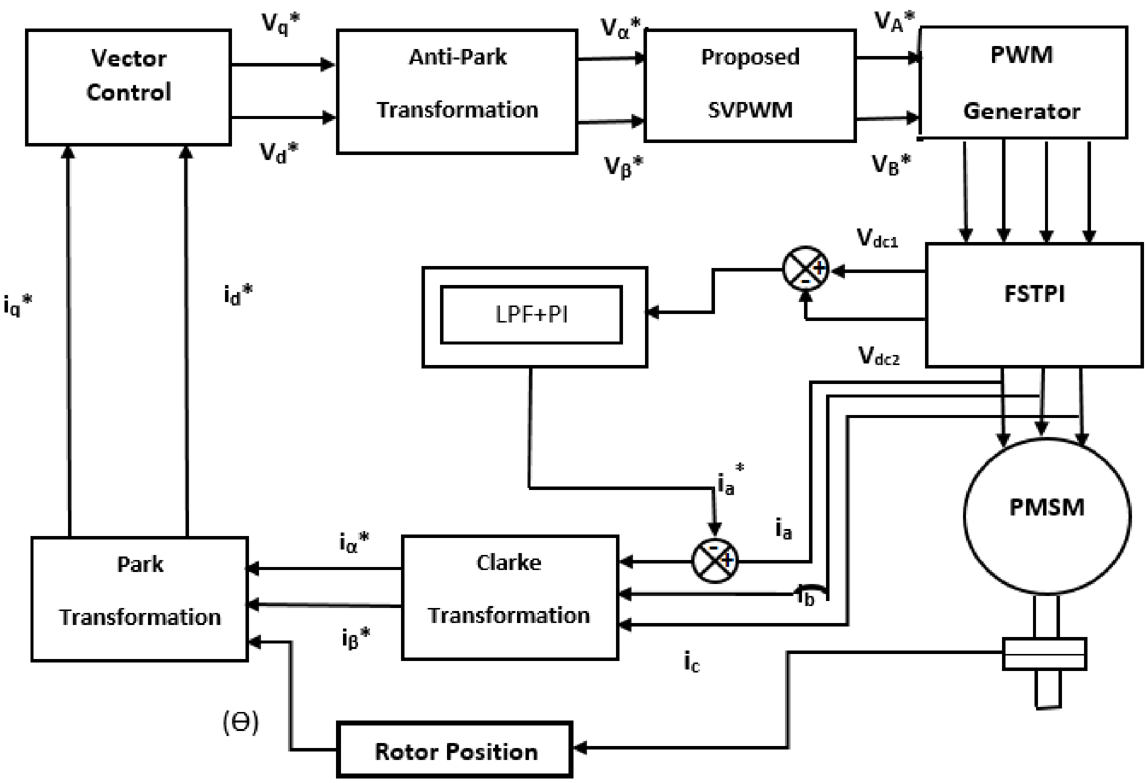


Fig.7.1. Block Diagram of Proposed FOC-based SVPWM of FSTPI-Fed PMSM Drive.

7.3. Proposed Compensation Method for Capacitor Voltage Fluctuation Control and PMSM Stator Current Regulation

For the effective speed control of a FSTPI based PMSM motor drive the schematic shown in figure .7.2. is developed.

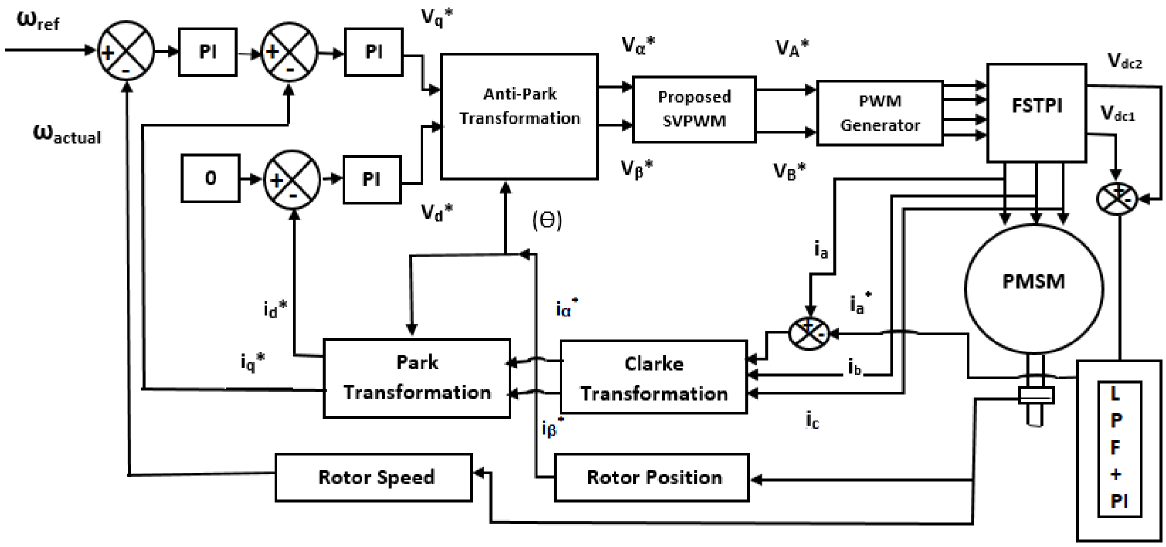


Fig. 7.2. Schematic for Proposed FOC-based SVPWM of FSTPI-Fed PMSM Drive.

7.3.1 SPEED ERROR BLOCK

In this block, the actual speed is compared with the reference speed and the error generated is sent to the PI controller for appropriate conditioning.

7.3.2 PI CONTROLLER BLOCK

The aim of the Proportional-Integral (PI) Controller is to minimize the speed error in the control system. The proportional gain (K_P) is set to provide a quick response to speed changes, while the integral gain (K_I) is used to eliminate steady-state error by accumulating past speed errors over time. The values chosen for these gains depend on the designer's judgment and are carefully tuned to achieve optimal speed response with minimal error. The output of the PI controller is then sent to the PWM block, where it generates the appropriate duty cycle to adjust the motor speed and maintain the desired set point.

7.3.3 PWM BLOCK

Pulse Width Modulation technique is applied mainly to change the duty ratio of an input quantity in order to control the output quantity at desired level. That is,

$$V_O = \alpha * V_i \qquad \text{……………..(7.1)}$$

where V_O: output voltage , V_i: Input Supply , α: Duty ratio; α may be defined as T_{ON}/T ; switching time period : $T = T_{ON} + T_{OFF} = 1/F_S$; F_S switching frequency.

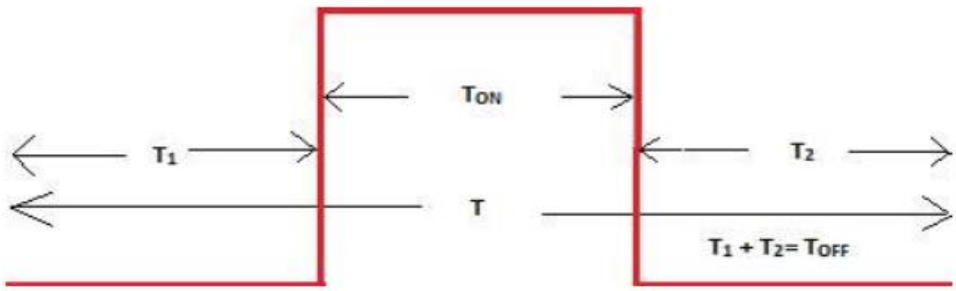


Fig. 7.3. One Time period of a PWM Pulse

7.3.4 Vector Control Block

After the speed error is calculated, the signal is fed to a Proportional-Integral (PI) controller, which generates the i_q reference signal. This i_q reference is then compared with the i_q-component of the PMSM stator currents. Simultaneously,

the d-axis component is compared with its respective reference. Each of these error signals is then processed through individual PI controllers for the d-axis and q-axis control loops. These two PI controllers generate the reference voltage components V_d for d-axes and V_q for q-axes, which are essential for maintaining the desired torque and flux within the PMSM. By precisely regulating these reference voltages, the control scheme ensures efficient and stable motor operation under various load conditions.

7.3.4 Inverse Park Transformation Block

Subsequently, the V_d and V_q components are passed through an inverse Park transformation, utilizing the rotor position to convert these components into the V_α and V_β reference voltages. This transformation enables the alignment of the control signals with the stationary reference frame, preparing the voltage components for further modulation and application to the PMSM stator windings.

7.3.5 Proposed SVPWM Block

The V_α and V_β signals are then used to generate the reference voltages V_A and V_B, which are precisely phase-shifted by 60^o degrees from each other. This phase shift is achieved through the proposed Space Vector Pulse Width Modulation (SVPWM) technique. To create the reference V_A and V_B signals, the angle and magnitude of the V_α and V_β components are first calculated, along with the sector of operation. The modulation index, sampling frequency, and sector information are then used to determine the appropriate vector timings for each sector. By combining these parameters, the reference V_A and V_B signals are generated, which are subsequently fed to the PWM generation block. These reference signals control the switching of the inverter, ensuring precise voltage output to drive the PMSM motor efficiently.

7.3.6. Capacitor Voltage Balancing and Current Control Block

A second-order low-pass filter, in conjunction with a Proportional-Integral (PI) controller, is utilized to mitigate the effects of capacitor voltage fluctuations in the system. The low-pass filter effectively attenuates high-frequency noise and smooth out voltage variations, allowing only the desired signal components to pass through. Meanwhile, the PI controller continuously adjusts the control signal to compensate for any steady-state errors and reduces the impact of the capacitor voltage fluctuations on the motor performance. Together, these components ensure stable operation of the Four-Switch Three-Phase Inverter (FSTPI)-fed Permanent Magnet Synchronous Motor (PMSM), improving the overall voltage balance and current regulation under dynamic load conditions.

A second-order low-pass filter (LPF) is commonly used in control systems to attenuate high-frequency noise and smooth out signals. The filter allows signals with a frequency lower than a specific cut-off frequency to pass through while reducing the amplitude of higher-frequency components. The transfer function of a second-order low-pass filter is typically represented as,

$$H(S) = \frac{{\omega_n}^2}{S^2 + 2\xi\omega_n S + {\omega_n}^2} \tag{7.2}$$

Where, ω_n is the natural frequency and ζ is the damping ratio. This filter is characterized by its ability to reduce oscillations and prevent signal distortion, which is particularly useful in applications requiring precise control, such as in the filtering of current or voltage signals in motor control systems. The second-order LPF is often employed in the control loops of inverters or motor drives to eliminate high-frequency harmonics and ensure stable system performance.

7.3.7. Vectors Utilization in The Proposed SVM Schemes

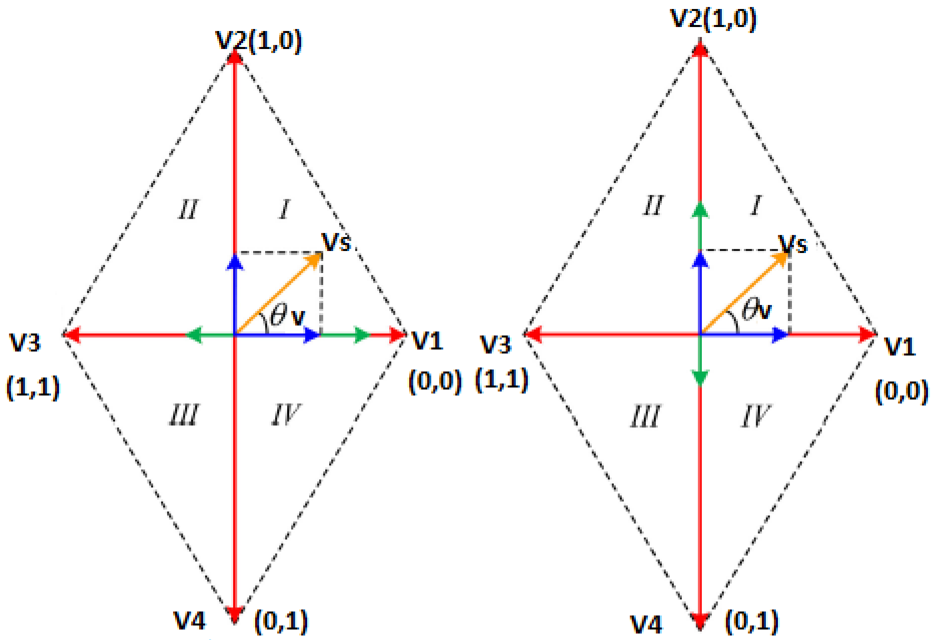


Fig.7.4. Space vector synthesis in TPFS inverter-fed PMSM drives: (a) using $(V_1 - V_3)$ to synthesize zero vectors (SVM1) and (b) using $(V_{2\_}V_4)$ to synthesize zero vectors (SVM2).

TABLE I
VECTORS UTILIZED IN THE TWO SVM SCHEMES

Angle(θ_V)	SECTOR	VECTORS	SVM
$0 \le \theta_V \prec 90$	**1**	$\overline{V}_1, \overline{V}_2, \overline{V}_3$	**SVM1**
$90 \le \theta_V \prec 180$	**2**	$\overline{V}_2, \overline{V}3, \overline{V}4$	**SVM2**
$-180 \le \theta_V \prec -90$	**3**	$\overline{V}_1, \overline{V}_3, \overline{V}_4$	**SVM1**
$-90 \le \theta_V \prec 0$	**4**	$\overline{V}_1, \overline{V}_2, \overline{V}_4$	**SVM2**

In the proposed Space Vector Modulation (SVM) scheme, two different SVM methods are merged to synthesize zero vectors for different sectors of the inverter. For Sector 1 and Sector 3, Zero Vectors are synthesized using Vector 1 and Vector 3. Similarly, for Sector 2 and Sector 4, Zero Vectors are synthesized using Vector 2 and Vector 4. This approach allows for more efficient voltage utilization and ensures that the inverter's output remains balanced and optimized. By strategically selecting and combining these zero vectors based on the sector, the proposed method minimizes harmonic distortion and reduces torque ripple, thus improving the overall performance of the FSTPI-fed Permanent Magnet Synchronous Motor (PMSM).

7.3.8. Switching Pattern of the proposed SVM

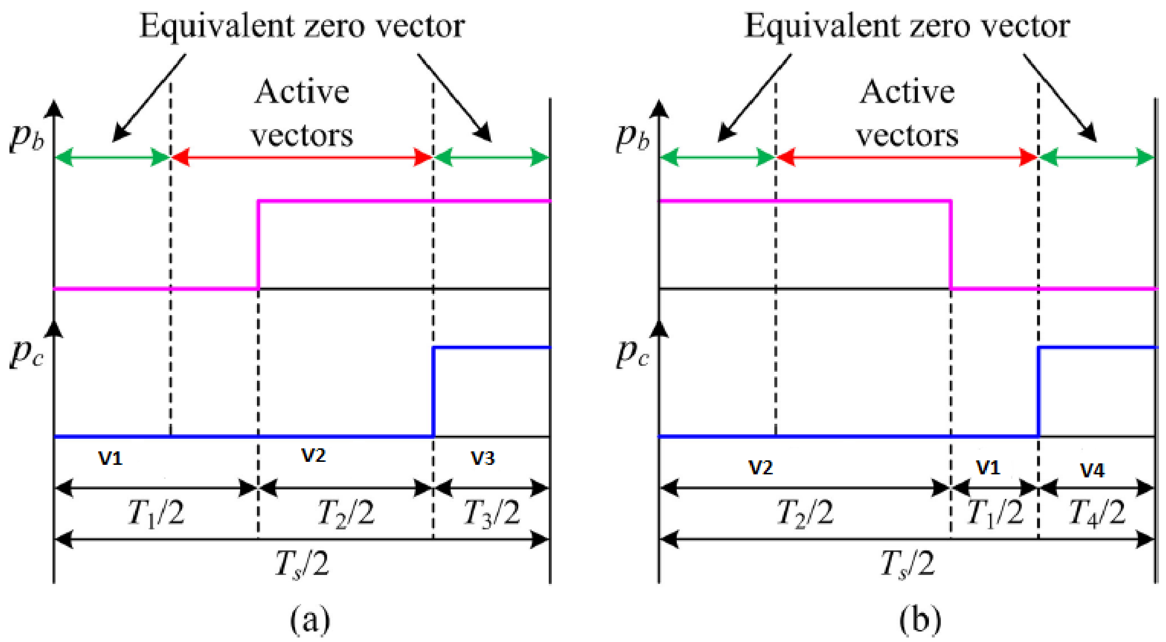


Fig.7.5. Switching sequences of the Proposed TPFS inverter-fed PMSM drives: (a) SVM1 and (b) SVM2.

In conclusion, the proposed control strategy effectively combines two Space Vector Modulation (SVM) methods to optimize the performance of the TPFS inverter-fed Permanent Magnet Synchronous Motor (PMSM) drive. By synthesizing zero vectors through a selective approach—utilizing specific switching sequences for each sector—the method achieves improved voltage utilization and reduced torque ripple. This dual SVM approach provides a more balanced and stable inverter output, minimizing harmonic distortion and enhancing the overall operational stability of the PMSM drive. The results of this study demonstrate that the merged SVM technique offers a robust solution for achieving precise control and improved performance in TPFS inverter applications, laying a strong foundation for further development of high-efficiency PMSM drive systems.

CHAPTER-8

MATLAB Modelling of FSTPI-Fed PMSM Drive Systems

8.1 Introduction

In this chapter, MATLAB-based modelling and simulations are presented to analyse and optimize the performance of a Permanent Magnet Synchronous Motor (PMSM) drive system fed by a Four-Switch Three-Phase Inverter (FSTPI). The modelling aims to explore the operational characteristics of the PMSM under different control approaches, starting with an open-loop control system.

8.1.1. Modelling of Open loop Control System of FSTPI-Fed PMSM Motor Drive:

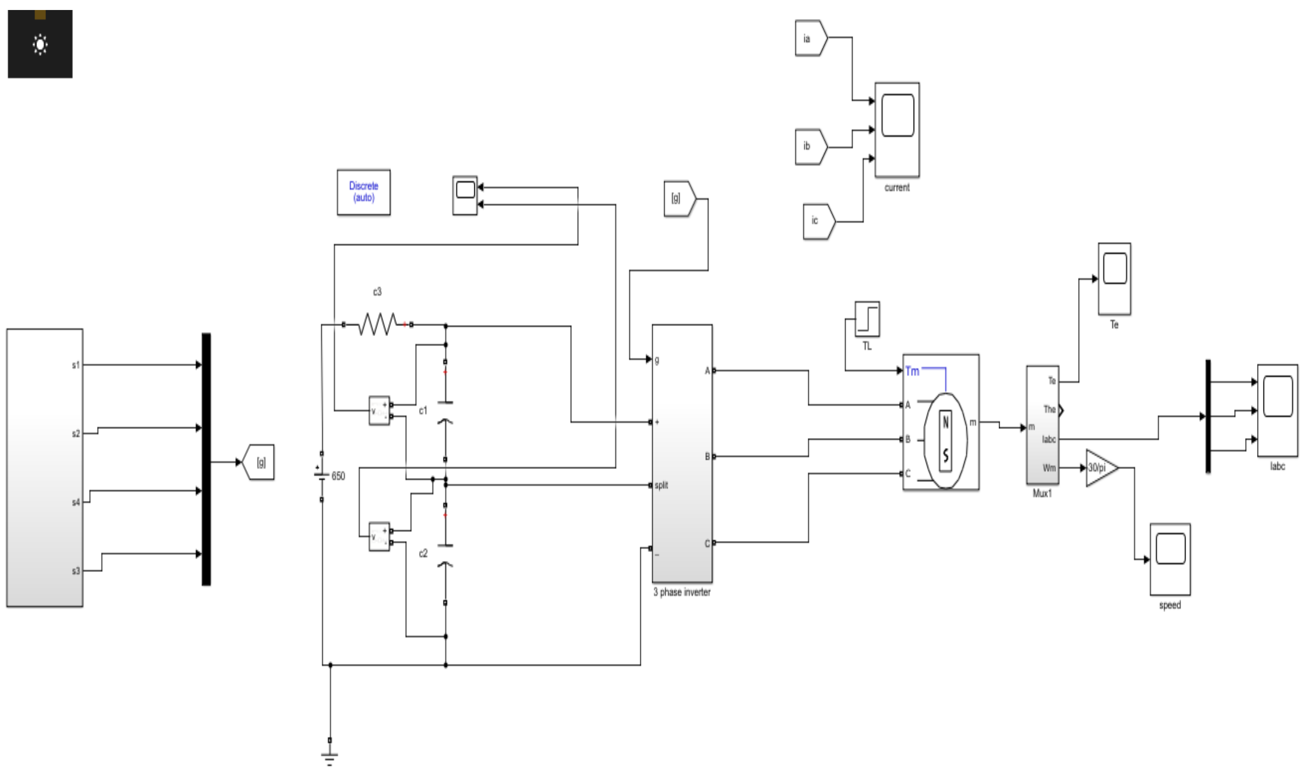


Fig.8.1. Open loop Control System of FSTPI-Fed PMSM Motor Drive

8.1.2. Modelling of Close-Loop Control System of FSTPI-Fed PMSM Motor Drive: FOC-Based SVPWM without Compensation of Capacitor Voltage Fluctuation

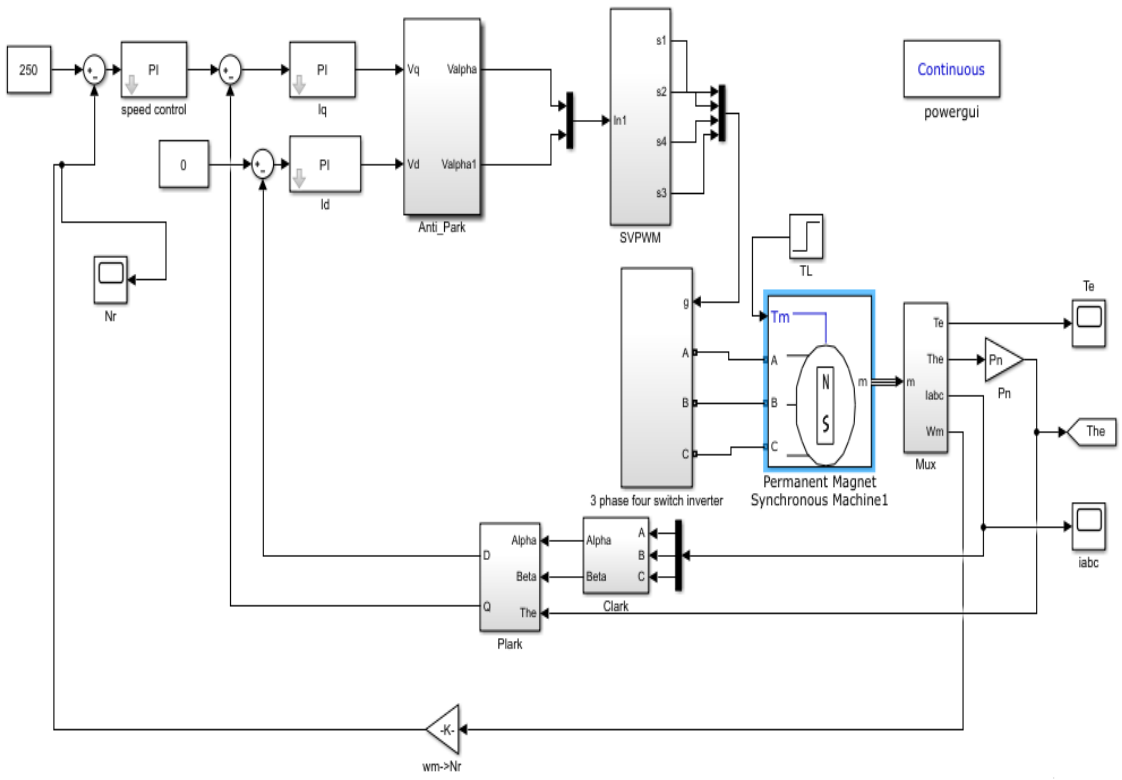


Fig.8.2. Close-Loop Control System of FSTPI-Fed PMSM Motor Drive: FOC-Based SVPWM without Compensation of Capacitor Voltage Fluctuation

8.1.3. Modelling of Close-Loop Control System of FSTPI-Fed PMSM Motor Drive: FOC-Based SVPWM with Capacitor Voltage Offset Suppression

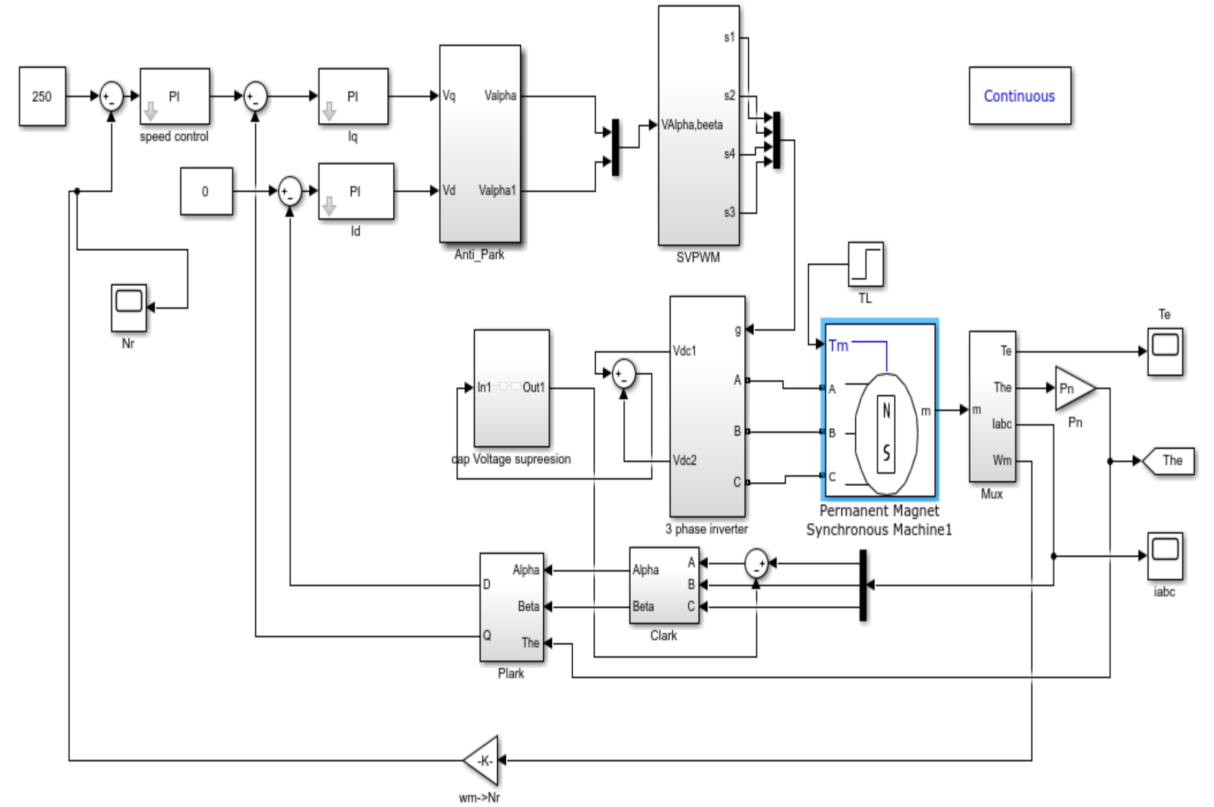


Fig.8.3. Close-Loop Control System of FSTPI-Fed PMSM Motor Drive: FOC-Based SVPWM with Capacitor Voltage Offset Suppression

8.1.4. Modelling of Four-Switch Three-Phase Inverter (FSTPI)

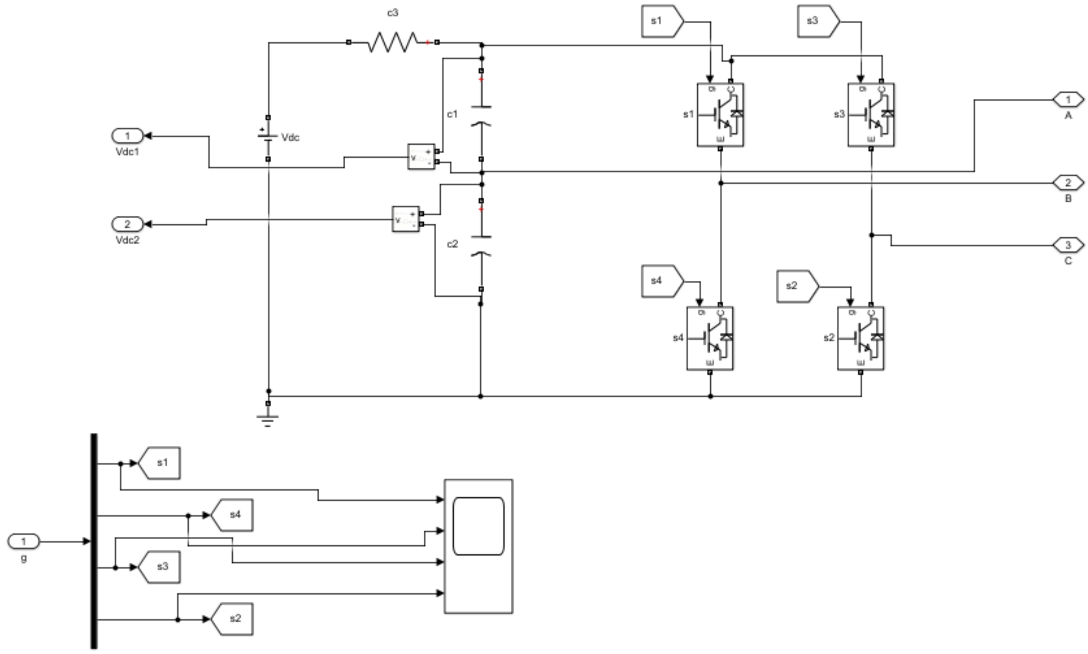


Fig.8.4. Modelling of Four-Switch Three-Phase Inverter (FSTPI)

8.1.4. Modelling of SVPWM

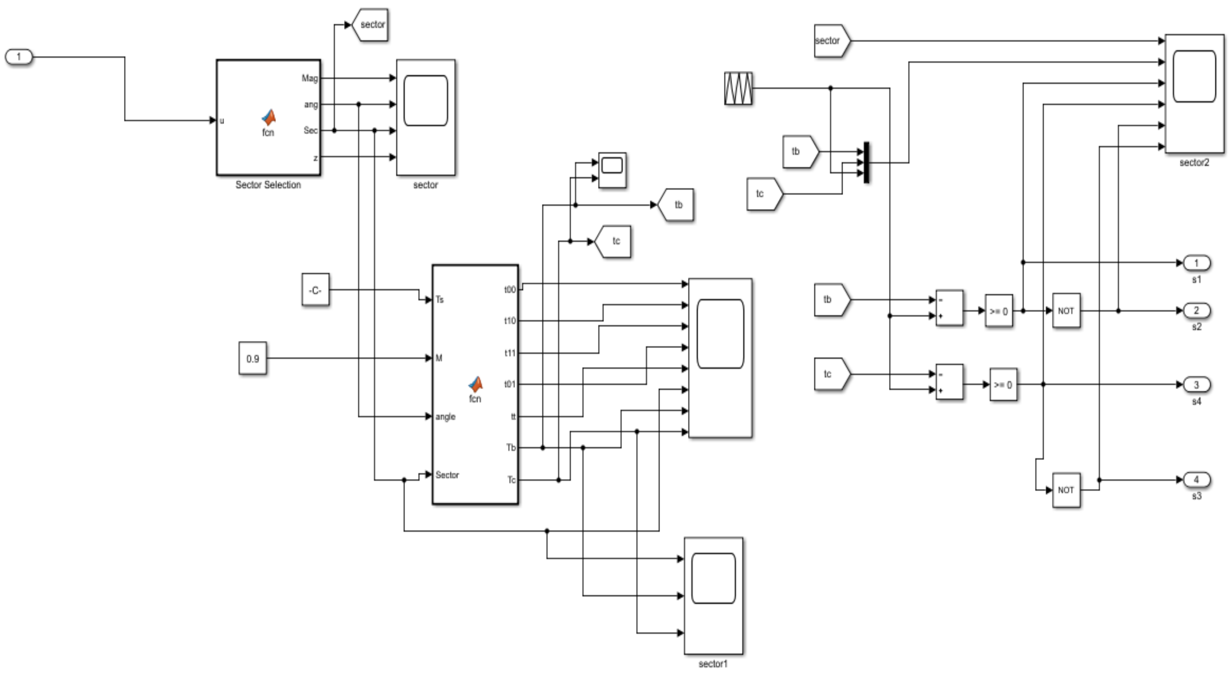


Fig.8.5. Modelling of of SVPWM Block for Four-Switch Three-Phase Inverter (FSTPI)

8.1.5. Modelling of *P-I controller*

P-I controller is the most primitive and highly used controller in power applications for its simplicity and easy applicability. The P-I controllers used in this model have been designed using mat lab toolbox as follows,

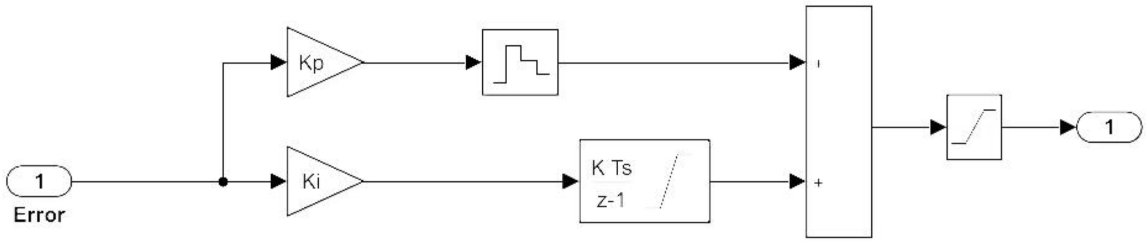


Fig.8.6. P-I Controller Mathematical Modelling

8.1.6. Modelling of Clarke Transformation

The Clarke Transformation, also known as α-β transformation, is a mathematical tool used in electric motor control and power electronics to simplify the analysis of three-phase systems. It converts three-phase quantities (e.g., currents, voltages) in the **a-b-c (three-phase) coordinate system** to an **α-β (two-phase) stationary reference frame**.

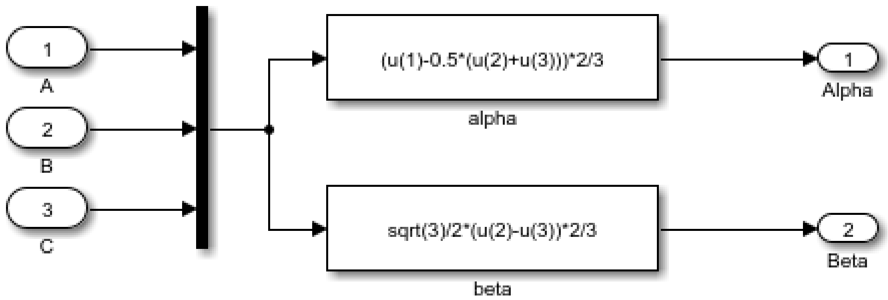


Fig.8.7. Modelling of Clarke Transformation

8.1.7. Modelling of Park Transformation

The Park Transformation, also known as the **d-q transformation**, is a mathematical process used in the control of AC motors and power systems to convert two-phase quantities (α-β frame) from the Clarke Transformation into a rotating reference frame that aligns with the rotor's magnetic field.

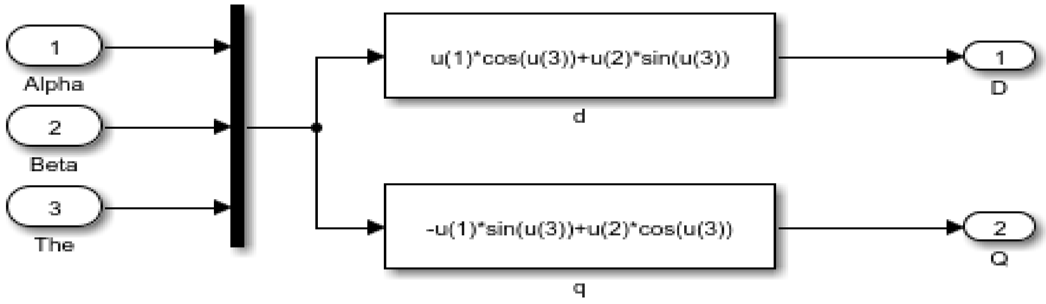


Fig.8.8. Modelling of Park Transformation

8.1.8. Modelling of Anti Park Transformation

The **Anti-Park Transformation**, or inverse d-q transformation, is used to convert signals from the rotating d-q reference frame (used in Field-Oriented Control, or FOC) back into the stationary α-β (two-phase) reference frame. This transformation is crucial in motor control applications, as it translates control signals from the simplified d-q frame to the actual voltages or currents that need to be applied to the motor.

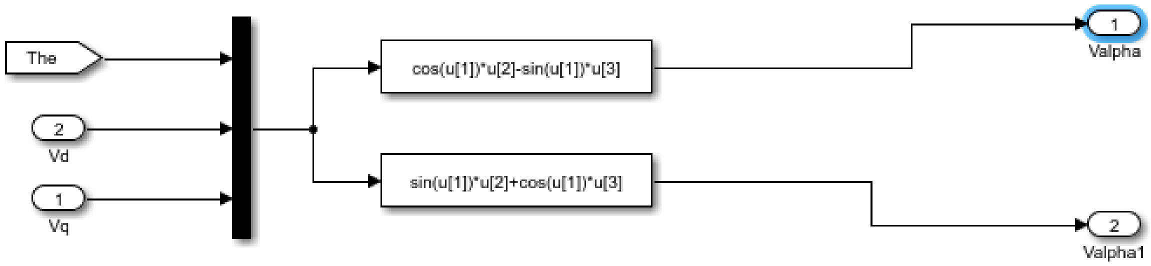


Fig.8.9. Modelling of Anti Park Transformation

8.1.9. MATLAB Function for Vector Timings of Each Sector

```
function [t00,t10,t11,t01,tt,Tb,Tc] = fcn(Ts,M,angle,Sector)

%M = sqrt(3)Vs/Vdc

switch Sector
    case 1
        t10 = M*Ts*sin(angle);
        t00 = 0.5*Ts - M*Ts*sin(angle - pi/3);
        t11 = 0.5*Ts - M*Ts*sin(angle + pi/3);
        t01 = 0;

    case 2
        t11 = -sqrt(3)*M*Ts*cos(angle);
        t10 = 0.5*Ts + M*Ts*sin(angle + pi/3);
        t01 = 0.5*Ts - M*Ts*sin(angle - pi/3);
        t00 = 0;

    case 3
        t01 = -M*Ts*sin(angle);
        t00 = 0.5*Ts + M*Ts*sin(angle + pi/3);
        t11 = 0.5*Ts + M*Ts*sin(angle - pi/3);
        t10 = 0;

    otherwise
        t00 = sqrt(3)*M*Ts*cos(angle);
        t10 = 0.5*Ts + M*Ts*sin(angle - pi/3);
        t01 = 0.5*Ts - M*Ts*sin(angle + pi/3);
```

Fig.8.10. MATLAB Function for Vector Timings of Each Sector

CHAPTER-9

SIMULATION RESULTS AND CONCLUSIONS

The developed topology was simulated on the Matlab / Simulink platform and satisfactory results were obtained which have been depicted in the following figures. The values assigned to the various parameters used in the proposed drive for simulation have been depicted in the table 6 and 7.

Table 9.1 : PMSM Motor Parameters

Parameters	Symbols	Values	Unit
No. of Pole	p	4	-
Stator Resistance	R_S	0.767	Ω
PM Flux (Peak)	ψ_m	0.1377	Wb
Q-axis Inductance	L_q	4.607	mH
D-axis Inductance	L_d	4.607	mH
Rated Power	P	1	kW
Rated Speed	N_S	1500	RPM
Rated Voltage	V	300	$Volt$
Rated Torque	T_{load}	10	Nm
Moment of Inertia	J	$6.876*10^{-3}$	$Kg-m^2$
Rated Stator Flux	ψ_S	0.3	Wb
Viscous Damping	B	$2.7504*10^{-3}$	Nms
Frequency	f	50	Hz

Table 9.2 : Details of other parameters used in the drive

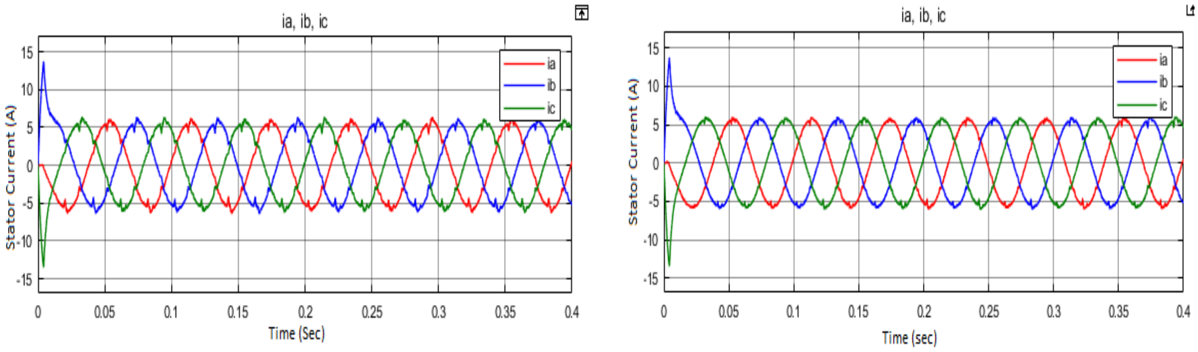
Input Voltage Of Inverter(V_{DC})	400 Volts
Switching period (T_S)	0.0001 sec
Reference Speed	250 RPM
Torque applied	10 Nm

Table 9.3 : Details of Controller parameters used in the drive

Dc Capacitors(C_1, C_2)	$2400 \mu f$
$PI - I_q$ Current controller	$K_p = 0.1, K_i = 1$
$PI - I_d$ Current controller	$K_p = 1, K_i = 10$
PI -torque controller	$K_p = 1, K_i = 5$
$LPF + PI$ -Capacitor offset	$K_p = 0.01, K_i = 0.01, \omega_n = \omega_r = 1(rad/\sec)$

9.4. Performance Analysis of Three-Phase Stator Current, Torque, and Speed at Low-Speed Range Operation:

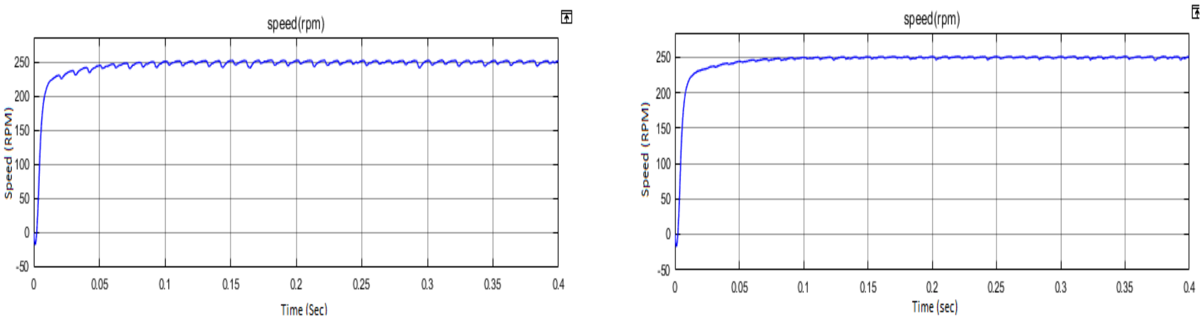
9.4.1. Experimental result for the Stator Current with V_{DC} **= 400 V**, T_{load} **= 10 Nm** and Speed (N) = **250 RPM**



(a) **(b)**

Fig.9.1. PMSM Stator Current (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

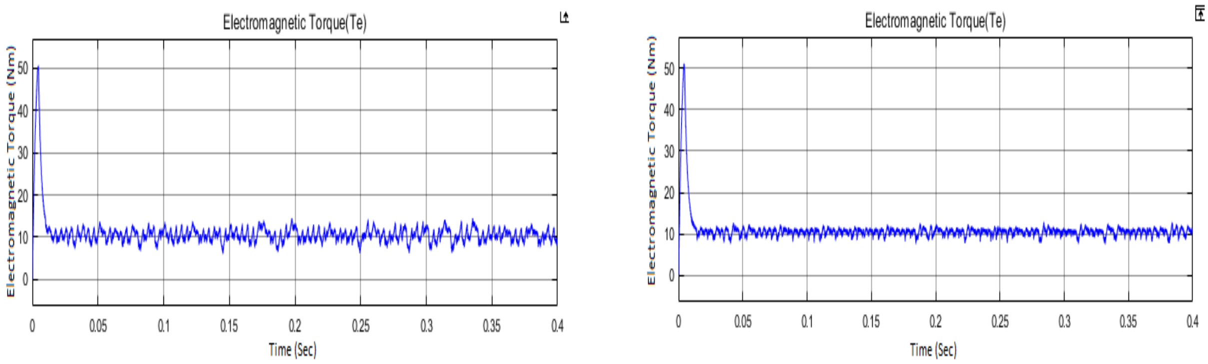
9.4.2. Experimental result for the Speed Response ,with V_{DC} **= 400 V**, T_{load} **= 10 Nm** and Speed (N) = **250 RPM**



(a) **(b)**

Fig.9.2. PMSM Speed Response (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

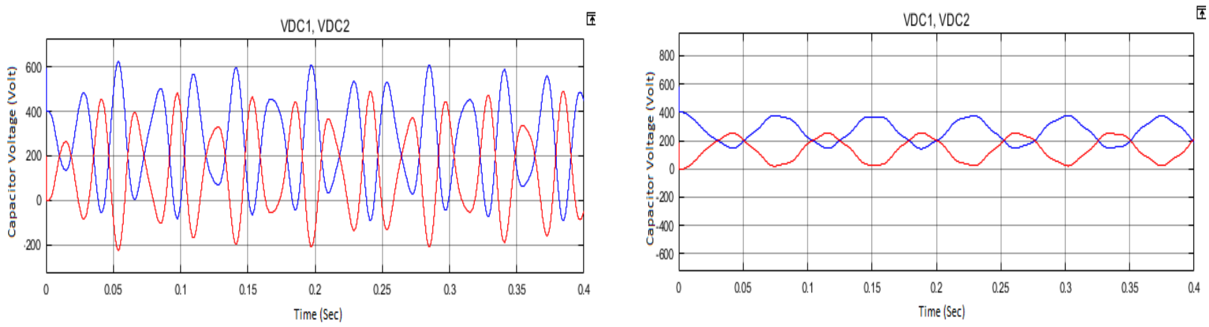
9.4.3. Experimental result for the Electromagnetic torque Response, with V_{DC} = **400 V**, T_{load} **= 10 Nm** and Speed (N) = **250 RPM**



(a) **(b)**

Fig.9.3. PMSM Electromagnetic Torque Response (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

9.4.4. Experimental result for the Dc link Capacitor Voltage Offset, with V_{DC} = **400 V**, T_{load} **= 10 Nm** and Speed (N) = **250 RPM**

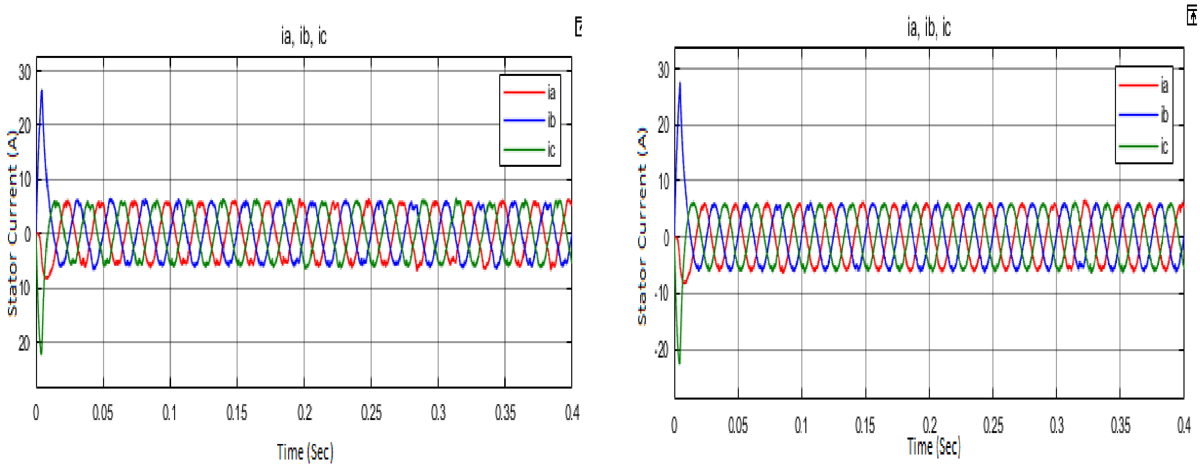


(a) **(b)**

Fig.9.4. The Dc link Capacitor Voltage Offset (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

9.5. Performance Analysis of Three-Phase Stator Current, Torque, and Speed at Medium-Speed Range Operation:

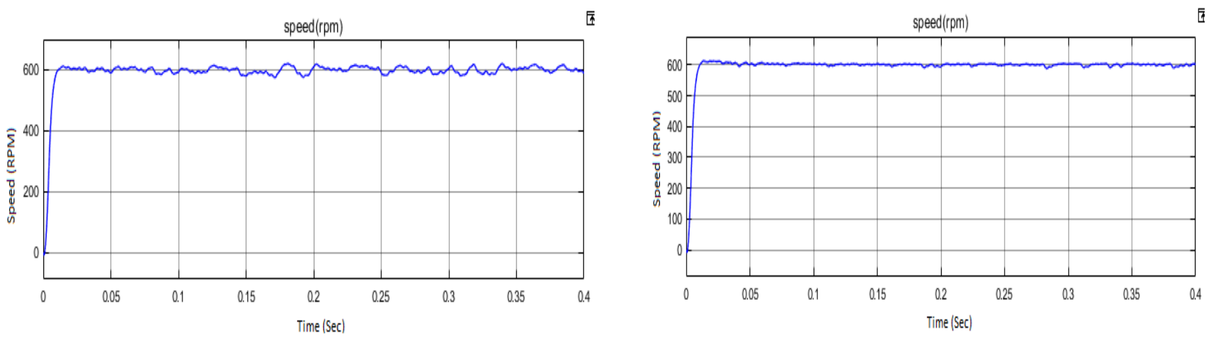
9.5.1. Experimental result for the Stator Current with V_{DC} **= 400 V**, T_{load} **= 10 Nm** and Speed (N) = **600 RPM**



(a) **(b)**

Fig.9.5. PMSM Stator Current (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

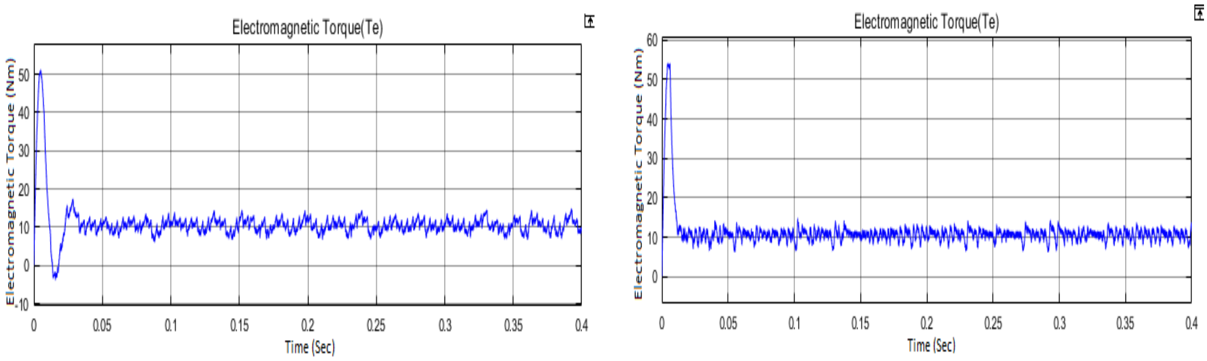
9.5.2. Experimental result for the Speed Response ,with V_{DC} **= 400 V**, T_{load} **= 10 Nm** and Speed (N) = **600 RPM**



(a) **(b)**

Fig.9.6. PMSM Speed Response (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

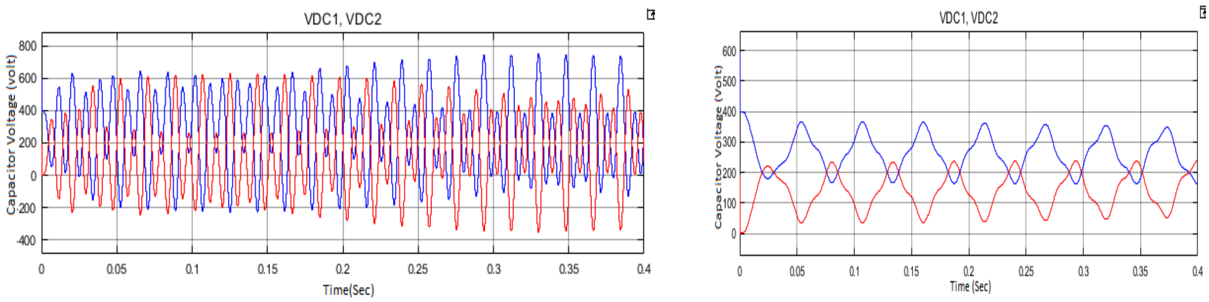
9.5.3. Experimental result for the Electromagnetic torque Response, with V_{DC} = **400 V**, T_{load} **= 10 Nm** and Speed (N) = **600 RPM**



(a) **(b)**

Fig.9.7. PMSM Electromagnetic Torque Response (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

9.5.4. Experimental result for the Dc link Capacitor Voltage Offset, with V_{DC} = **400 V**, T_{load} **= 10 Nm** and Speed (N) = **600 RPM**



(a) **(b)**

Fig.9.8.The Dc link Capacitor Voltage Offset (a) Without Capacitor Voltage Offset Suppression, (b) with Capacitor Voltage Offset Suppression

9.6. Results Of The Simulation And Discussion

In this study, the FSTPI-fed PMSM drive system was simulated under two configurations and two speed settings:

Case 1: Low-Speed setting (250 rpm)

- **Configurations**:
  - Configuration 1: FOC with SVPWM
  - Configuration 2: FOC with SVPWM and capacitor voltage suppression technique
- **Parameters**:
  - Load torque: 10 Nm
  - DC link voltage: 400 V
- **Observations**:
  - Configuration 1 showed noticeable capacitor voltage fluctuations.
  - Configuration 2 (with capacitor voltage suppression) achieved:
    - Reduced capacitor voltage fluctuations
    - Smoother stator currents
    - Reduced torque ripple
    - A more stable and smoother speed curve

Case 2: Medium-Speed setting (600 rpm)

- **Configurations**:
  - Configuration 1: FOC with SVPWM
  - Configuration 2: FOC with SVPWM and capacitor voltage suppression technique
- **Parameters**:
  - Load torque: 10 Nm
  - DC link voltage: 400 V
- **Observations**:
  - In Configuration 1, capacitor voltage fluctuations were more severe at this medium speed.
  - Configuration 2 (with capacitor voltage suppression) showed:
    - Reduced capacitor voltage fluctuations, though not as effectively as in Case 1 (250 rpm)
    - Higher torque ripple and a less smooth speed curve compared to the low-speed case

9.7. Conclusion

1. The capacitor voltage suppression technique is effective in both speed settings, but it is more successful at reducing voltage fluctuations, torque ripple, and speed instability at low speeds (250 rpm).

2. At medium speed (600 rpm), while some improvements are seen with the suppression technique, the torque ripple remains higher, and the speed curve is less stable compared to the low-speed case.

3. A comparative analysis was also conducted between the FSTPI-fed PMSM drive and a conventional six-switch inverter-fed PMSM drive. Results indicate that the FSTPI configuration exhibits higher torque ripple compared to the six-switch inverter under similar operating conditions. However, this increased torque ripple in the FSTPI-fed drive is within acceptable limits and can be considered manageable for applications where a simplified inverter topology is preferred. This trade-off highlights the effectiveness of the FSTPI design in reducing component count and complexity while delivering satisfactory performance, particularly when paired with the capacitor voltage suppression technique to further improve torque ripple and current waveform smoothness.

CHAPTER-10

FUTURE SCOPE

The proposed model has been found to behave satisfactorily based on simulation results. However its hardware implementation is necessary in order to ascertain its practical viability.

The simulation results indicate that, while the capacitor voltage suppression technique improves torque ripple and current smoothness in the FSTPI-fed PMSM drive, the speed response remains somewhat stiff, especially at higher speeds. Compared to the smoother performance of the six-switch inverter, this suggests a need for further optimization in the FSTPI drive to achieve smoother speed control across varying conditions.

Moreover it is also noted that the current response of the three phases contains a lot of noise which needs to be suppressed further. Therefore appropriate noise reduction technique needs to be employed for better phase current profile.

There is a need to improve the capacitor voltage suppression methods to better control voltage fluctuations at higher speeds, which would help in making the current and torque smoother.

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