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ABSTRACT

This thesis investigates and compares the modelling, control mechanisms, and performance outcomes of FOC and PI-SVPWM-based DTC techniques for a PMSM drive system. The increasing demand for efficient control strategies in high-performance electric drive applications can offer fast dynamic response, better steady-state performance and reduced torque ripple. In this work, the mathematical modelling of PMSM is developed using abc and d-q reference frame transformations. An analysis of traditional DTC is conducted to identify key drawbacks, particularly its variable switching frequency and elevated ripples in both flux and torque.

The proposed PI-SVPWM-based DTC method and FOC technique are implemented in MATLAB/Simulink environment under similar operating conditions for fair performance evaluation. The simulation results are analyzed analysis between FOC and proposed DTC technique is also carried out to evaluate their dynamic and steady-state performance.in terms of speed, electromagnetic torque and transient characteristics. The obtained results show that, in comparison to conventional DTC, the suggested PI-SVPWM-based DTC technique offers better steady-state performance. The FOC technique offers smooth current control and stable operation. Therefore, the proposed control strategy can be considered an effective solution for high-performance PMSM drive applications.

Chapter 1

INTRODUCTION

1.1. *Introduction to Electric Drives:*

Electric drive systems have become an essential part of modern industrial and commercial applications because they provide efficient conversion of electrical energy into controlled mechanical motion. Depending on the application, advanced control algorithms combined with power electronic converters and electric machines ensure precise regulation of speed, torque and position. Owing to their high efficiency and dependability, electric drives are extensively employed in electric vehicles, renewable energy setups, aerospace technologies, conveyor networks and industrial robotics [1].

The continuous growth of automated manufacturing and energy-efficient technologies has significantly increased the need for high-performance motor drive systems. The straightforward control structure made conventional DC motors made them the go-to option for variable-speed tasks, but the brushes and commutators make the maintenance requirements higher and the system reliability lower. Modern industries are increasingly using AC motor drives to overcome these drawbacks [1].

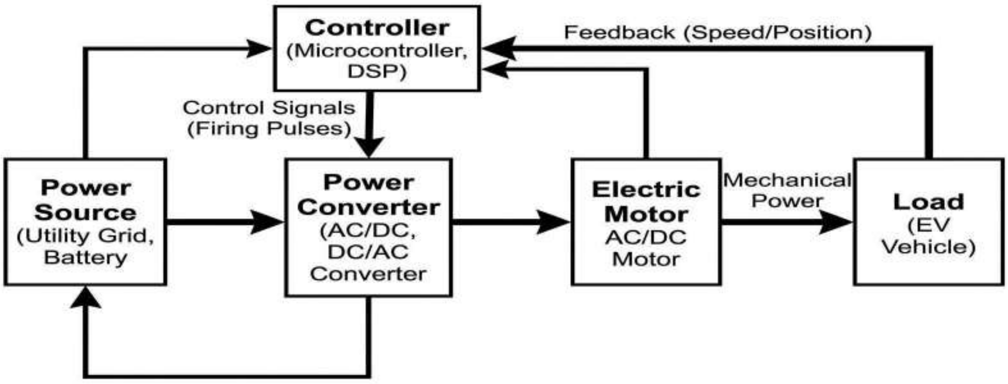

Fig.1.1: Basic Block Diagram of Electric Drive System

Among the available AC machine technologies, the PMSM is of great interest because of it because of its high efficiency, compact structure, and excellent torque-producing ability. Permanent magnets on the rotor eliminate the need for external field excitation, thereby reducing rotor losses and improving overall energy conversion efficiency [2]. These benefits have led to a wide application of PMSMs in electric vehicles, servo drives, home applications and precision motion control applications [2].

The key factor that affects the performance of PMSM drives is the control strategy employed for regulating speed, torque and the flux. In PMSM drive applications, various control methods like Scalar Control, FOC and DTC are used. Among these approaches, the FOC provides independent control of the torque and flux components through coordinate transformations, which results in smooth speed regulation and reduced torque ripple. On the other hand, DTC directly controls the torque and stator flux, which results in a faster dynamic response and a relatively simple control structure [3]-[5].

To further improve drive performance, advanced control techniques incorporating PI controllers and SVPWM have been investigated. In this thesis, both FOC and a better DTC method are implemented and compared with PI controllers and SVPWM. This technique is primarily used to minimize torque ripples and improve the dynamic response enhancement of the PMSM [9].

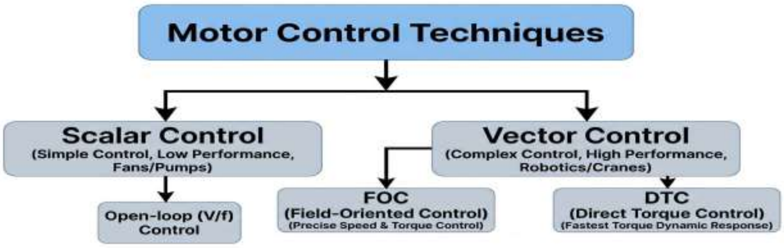

Fig.1.2: Classification of Motor Control Techniques

1.2. *Permanent Magnet Synchronous Motor (PMSM):*

Within the broad category of AC machines, Permanent Magnet Synchronous Motors (PMSMs) stand out and are extensively favored for their exceptional dynamic capabilities, enhanced efficiency, substantial power density, and space-saving design. Unlike conventional synchronous machines, PMSMs utilize permanent magnets mounted or embedded in the rotor to generate the excitation field. Hence, the losses in the rotor excitation are eliminated, increasing the efficiency and reducing the thermal stress [2].

The stator construction of a PMSM is similar to the stator of a conventional three-phase AC machine. When the stator windings are given balanced three-phase voltages, a rotating magnetic field is produced in the air gap. This field rotates and interacts with the magnetic field of the rotor magnets. This interaction produces an electromagnetic torque. Because the rotor magnetic field rotates at the same speed as the stator field, the machine works under synchronous conditions and is called a synchronous motor [2].

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Due to their excellent operating features, PMSMs are widely used for high-efficiency and precision speed regulation applications. Popular application areas vary from electric vehicles, robotic systems, servo drives, aerospace equipment, computer numerical control (CNC) machines and renewable energy systems. PMSMs have advantages over induction motors in terms of higher power density, lower maintenance requirements, lower losses and better torque/inertia ratio [2].

The drive control of PMSMs is usually achieved by means of high-end control techniques like FOC and DTC. Such a control technique leads to a dynamic response of the motor and ensures accurate speed and torque control of the motor [5]. In recent times, PMSM drives have become very popular for research and practical purposes due to their compatibility with digital control schemes.

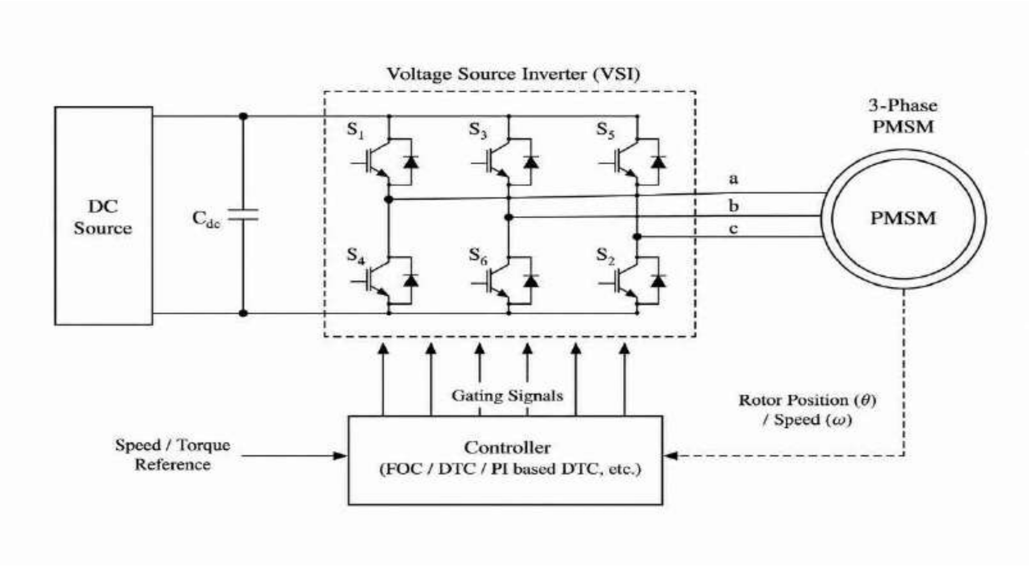

Fig.1.3: Configuration of the PMSM Drive System

1.3. *Types of PMSM:*

PMSM can be categorized according to the placement of permanent magnets within the rotor structure [7].

1.3.1. Surface Mounted PMSM (SPMSM):

In a Surface Mounted PMSM, permanent magnets are attached directly to the outer surface of the rotor. The SPMSM is simple in rotor design and ensures smooth performance with minimal torque ripples. This kind of motor is used extensively in low and medium-speed operations because of its simplicity and easy control system. The distribution of rotor flux in SPMSM is almost sinusoidal, making the motor efficient and minimizing harmonics. However, because the magnets are exposed on the rotor surface, mechanical robustness becomes a concern at very high operating speeds [12].

Advantages of SPMSM:

- *Simple construction*
- *Smooth torque characteristics*
- *Easy control implementation*
- *Low rotor losses*

Limitations of SPMSM:

- *Lower mechanical strength at high speed*
- *Limited field weakening capability*

1.3.2. Interior PMSM (IPMSM):

In an Interior PMSM, the permanent magnets are embedded within the rotor core rather than being mounted on its surface. The configuration of interior PMSM ensures higher mechanical strength and enables operations at increased rotational speeds. Moreover, interior PMSM has enhanced field weakening characteristics, making it appropriate for use in electric *vehicles and high-speed industries. Due to rotor saliency in IPMSM, both reluctance torque and magnetic torque contribute to total electromagnetic torque production. This results in improved torque capability and higher efficiency [12].*

Advantages of IPMSM:

- *High mechanical strength*
- *Better field weakening operation*
- *Higher torque capability*
- *Suitable for high-speed applications*

Limitations of IPMSM:

- *Complex rotor construction*
- *Higher manufacturing cost*

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1.4. *Field Oriented Control (FOC):*

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Field Oriented Control (FOC) or vector control is a common control strategy for high-performance AC motor drives. The main objective of this approach is to independently control the motor flux and the electromagnetic torque, in order to achieve control features similar to those of the separately excited DC motors for AC machines. Therefore, FOC provides accurate speed regulation, smooth torque production and improved dynamic behaviour of the drive system [3],[4].

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The basic principle of operation of FOC is based on the transformation of the three phase stator currents into synchronously rotating d-q reference frame using the Clarke and Park transformations. In that reference frame, the d-axis current component is associated with flux generation and the q-axis current component is associated with electromagnetic torque production. Therefore, through independent control of these vectors, improved performance can be realized. The components of the FOC method include current controllers, speed controllers, coordinate transformations, pulse width modulation technique, and inverter switching systems [4]. PI controllers are commonly employed due to their straightforward design and effective control performance. SVPWM is frequently integrated into the FOC algorithm in order to produce pulses for the inverter with low harmonic distortion and increased efficiency of DC bus utilization [9].

FOC provides several advantages such as low torque ripple, smooth operation, high efficiency, and precise control of the motor speed. Because of these merits, FOC finds wide application in electric cars, robots, servomechanisms, computer numerical control machine tools, and automated manufacturing processes [4].

However, despite its strengths, FOC does have its own drawbacks. One limitation of the control scheme for FOC lies in its complexity due to multiple coordinate transformation processes and the precise determination of motor parameters. Another problem associated with FOC is the slower dynamic response compared to that of Direct Torque Control (DTC) [5].

Hence, further research into different control strategies is being conducted to improve the efficiency of motor drive systems. In this thesis, the FOC approach is applied for performance analysis and comparison with the proposed improved version of the DTC approach.

Table.1.1: Advantages and limitations of FOC

Advantages	**Limitations**
Smooth torque response	Complex Control Structure
Low torque ripple	Requires coordinate transformation
Accurate speed control	Parameter sensitivity
Better steady-state performance	Higher computational requirement

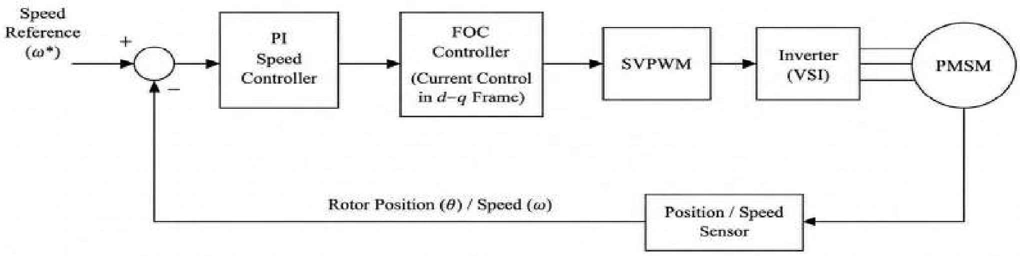

Fig.1.4: FOC-Based PMSM Control Scheme

1.5. *Direct Torque Control (DTC):*

Direct Torque Control (DTC) is a high performance control method developed for AC motor drives in order to provide fast torque response and simple control implementation. Unlike conventional vector control approaches, DTC directly controls the electromagnetic torque and stator flux without inner current control loops. This feature gives fast dynamic performance and decreases the complexity of control structure [5],[6]. With respect to the DTC approach, both stator flux and torque are constantly estimated from stator voltage and current values. The estimated quantities are then compared with their respective reference values, and their differences are passed to the hysteresis comparators. According to the results obtained from the comparators together with the present position of the stator flux vector, the proper switching state of the inverter is chosen from the switching table [6].

The main difference between FOC and DTC is that in DTC, no coordinate transformations, current controllers, or pulse width modulation are required. As a result of the simple control algorithm utilized, DTC can give instantaneous responses of torque and superior transient performance. For this reason, DTC is applicable for cases where instant acceleration and high dynamics are demanded [5].

In the conventional DTC method, the rotor flux and electromechanical torque are estimated on the basis of the stator voltages and stator currents. The estimated values are compared to the reference values for them, respectively, and the resultant error values are then fed to the hysteresis controllers. Depending upon the output of the hysteresis controller and position of the rotor flux vector, a particular inverter voltage vector is chosen from a preset switching table. [6,5].

One of the advantages of DTC is that it can provide a very fast transient response. This is possible since the states of inverter switching will only have to be chosen. Without the need for current regulation and pulse width modulation, the computational requirements are reduced, and the overall control architecture becomes simpler.

Hence, DTC is very appropriate for the applications of requiring fast torque response and high dynamic performance [5].

Although DTC offers excellent dynamic performance, however, some limitations do not make it suitable for use in precision drive systems. Some of the limitations associated with the traditional DTC include torque ripples, flux ripples in stator, current ripples, and varying switching frequencies [15].In order to address such limitations, improved DTC techniques that employ PI controllers and SVPWM have been suggested [8].

This thesis proposes and implements a PI-SVPWM based DTC scheme for PMSM drive applications. This proposed approach targets minimizing torque ripple, improving the flux regulation and enhancing the dynamic and steady-state performance of the PMSM drive system. Moreover, a comparison between the proposed DTC technique and FOC is conducted to assess their performance under the same operating conditions.

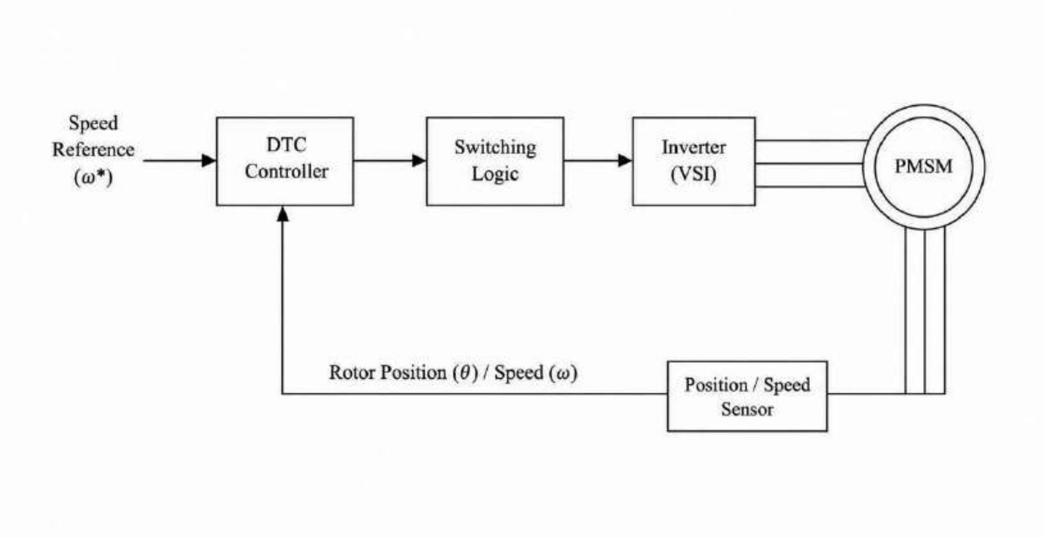

Fig.1.5: DTC-Based PMSM Control Scheme

1.6. *Comparative Analysis of FOC and DTC:*

FOC and DTC are the two best-known control algorithms used by high performance PMSM Drives. Although both methods aim to regulate motor speed and electromagnetic torque effectively, their operating principles differ significantly [3],[5]. In FOC, principles of vector control are utilized whereby the currents flowing through the stator windings are represented in terms of d-axis and q-axis components using Clarke and Park transformations. In this way, d-axis currents are responsible for controlling the flux, while q-axis currents control the generation of torque [4]. The main difference between FOC and DTC lies in the fact that the current d-component in the FOC system is responsible for flux control, while the current component q controls the electromagnetic torque [4], whereas DTC does not use any coordinate transformations and current control loops to manage stator flux and electromagnetic torque [5]. Instead, it utilizes hysteresis controllers and switching tables.

In practical motor drive applications, the choice between FOC and DTC mainly depends on system requirements. The applications that demand smooth steady-state operation and accurate speed control typically use FOC. On the other hand, applications that need fast dynamic responses and a simple control structure tend to make use of DTC control [10]. Recent developments in PI-controller and SVPWM-based DTC methods have significantly improved steady-state behaviour and reduced torque ripple, making DTC a strong alternative to conventional FOC strategies [8]. Thus, there exists a need to conduct a comparatives analysis between FOC and the improved DTC approach.

In this thesis, a comparative performance evaluation of FOC and PI-SVPWM-based DTC is carried out under identical operating conditions to examine their transient characteristics, torque response, and ripple performance.

Table.1.2: Comparison Between FOC & DTC

Parameter	**FOC**	**DTC**
Control Principle	Vector Control	Direct Torque &Flux Control
Dynamic Response	Moderate	Fast
Torque Ripple	Low	Higher
Switching Frequency	Constant	Variable
Complexity	High	Moderate
Current Controller	Required	Not Required
Steady-state performance	Better	Moderate
Implementation	Complex	Simple

1.7. *Introduction to Space Vector Pulse Width Modulation:*

Space Vector Pulse Width Modulation (SVPWM) is an advanced inverter switch control technique that is commonly employed in contemporary AC drives. The benefits of using SVPWM compared to sinusoidal PWM techniques include higher DC bus voltage utilization, reduced harmonic content and improve performance of the inverter [9]. According to the SVPWM algorithm, the switching states of the three-phase voltage source inverter are modeled as voltage vectors in a two-dimensional coordinate plane. The desired reference voltage vector can thus be created through the proper combination of the active and zero vectors during each switching cycle [9].

The basic concept behind the implementation of SVPWM is the representation of the voltages generated by the three-phase inverters in a two-dimensional coordinate plane using voltage vectors. A conventional three-phase inverter has eight switching states comprising six voltage vectors that are active and two voltage vectors that are null. The vectors split the space vector plane into six sectors. Based on where the reference vector is situated, the switching sequence and duty cycle can be determined to provide the necessary output voltage [9].

In comparison with sinusoidal PWM techniques, SVPWM offers many advantages, including high voltage utilization, low switching losses, low THD, and efficient inverter operation. Due to these advantages, SVPWM is extensively used in PMSM drive applications, particularly for FOC and advanced DTC techniques [9]. For this thesis, SVPWM is employed alongside the PI-based DTC method in order to optimize inverter switching and improve the control performance of motor.

1.8. *Objective of Thesis:*

The main aim of the thesis is to carry out a comparative analysis between two different control strategies for PMSM drives, namely FOC and DTC.

The work focuses on improving the dynamic as well as steady-state performance of the PMSM drive system in different working conditions. Special attention is paid to reducing the torque ripple naturally present in conventional DTC schemes. To solve this problem, a modified DTC methodology with proportional integral (PI) controllers and SVPWM is developed and implemented. The PI controllers for speed, torque and flux regulation are integrated for improved control accuracy, system stability and overall drive performance.

The following are the major objectives of the thesis:

- To understand the principles of operation and modelling of PMSM.
- To analyze the performance of the FOC technique.
- To study the conventional DTC method.
- To conduct a performance comparison between FOC and advanced DTC.
- To analyze speed response, torque ripple, and flux characteristics of the PMSM drive.
- To implement and simulate the complete system using MATLAB/Simulink.

1.9. *Organization of Thesis:*

This thesis is composed of seven chapters covering the modelling, control, implementation, and comparative analysis of PMSM drive control techniques.

Chapter 1 covers the general introduction about the electric drives, PMSM, FOC, and DTC. A Comparative study regarding both the FOC and DTC techniques is also covered here. Besides, the drawbacks of the conventional DTC techniques and the introduction of SVPWM are included in this chapter.

Chapter 2 analyzes the literature review of PMSM drives along with various motor control techniques that were developed during previous research studies. The research gap and need for the current study are determined by the review of the various methods of FOC, DTC, SVPWM and torque ripple reduction.

Chapter 3 develops a mathematical modelling of the PMSM drive system. The equations related to the electrical and mechanical behavior of PMSM, along with Clarke and Park transformations, flux linkage equations, and electromagnetic torque equations, are discussed in detail. This chapter gives the basic knowledge to implement various control techniques.

Chapter 4 describes the implementation of the Enhanced DTC approach using a PI controller and SVPWM. In this chapter, the conventional hysteresis-based DTC method is modified by integrating a PI controller for controlling the variables namely torque, speed, and flux of PMSM.

Chapter 5 deals with the implementation of FOC for PMSM drive applications. The chapter describes d-q axis currents control, PI controllers, SVPWM, and a MATLAB/Simulink model for the proposed FOC-based PMSM drive system

Chapter 6 contains the simulation results and comparative performance analysis of FOC and improved DTC techniques under different operating conditions. Several performance indices, including speed responses, electromagnetic torque, rotor flux, torque ripples and stator current waveforms, are used for comparisons.

Chapter 7 conclude the entire work in this thesis paper with a summary of conclusions made from the entire comparative analysis. Future improvement possibilities are also considered in this final chapter.

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Chapter 2

LITERATURE REVIEW

2.1. *Introduction:*

In this chapter, a literature review concerning previous research in relation to PMSM drives and innovative schemes for motor control is provided. In particular, the focus is placed on papers dealing with FOC, DTC control schemes and their sophisticated counterparts aimed at improving motor drive performance. Fast dynamic performance, minimized torque ripple, superior speed regulation and increased steady-state performance have been investigated using different control methods [2],[5]. In recent decades, a number of improvements have been made in conventional DTC, such as SVPWM implementation, PI controllers, predictive control laws and intelligent optimization. However, all these advancements have been aimed at minimizing torque ripple as well as frequency-related restrictions of classical DTC schemes [10]. This chapter overviews the significant contributions documented in the previous literature concerning PMSM modelling, FOC techniques, DTC methods, SVPWM strategies, and torque ripple reduction techniques. Advantages and disadvantages of various approaches are discussed to identify the research gap and motivation behind the proposed work.

2.2. Review on Field Oriented Control (FOC):

The concept of Field-Oriented Control was introduced by Blaschke in 1972 and represented a major advancement in AC motor drive technology. This approach helped attain independent control of flux and torque components and thus allowed AC machines to attain a performance level that could match that of DC motors with separate excitation systems. The study showed the improvement of dynamic response and exact speed control of electrical drive systems. But the need for coordinate transformations and parameter estimation contributed to the implementation complexity [3].

Bose emphasized the application of PI-controller-based FOC techniques for PMSMs. The author clarified that the PI controller increases steady-state accuracy and provides smooth speed control under varying operating conditions. This research also noted the role of current in current regulation in the d-q reference frame for improved drive performance. The proposed method reduced current distortion, but the system needed an accurate tuning of controller parameters [4].

Krishnan analyzed the mathematical modelling and implementation of FOC for Permanent Magnet Synchronous Motors. His research showed that FOC ensures reduced torque ripple and improved speed regulation compared to conventional scalar control methods. The author also explains how PWM techniques could be used for inverter control in PMSM drives. However, the computational complexity of the control system remained comparatively low [2].

However, the recent research work is based on the optimization of the performance of FOC using intelligent optimization algorithms, adaptive control schemes, and high-end PWM techniques. It has been found that the use of SVPWM contributes to better utilization of inverters as well as minimizing the harmonics in PMSM drives [9].

2.3. Review on Direct Torque Control (DTC):

Direct Torque Control (DTC) highly appreciated in PMSM drives owing to its fast transient behavior and relatively simple structure. In contrast to vector control methods, where the torque and stator flux are indirectly controlled by means of multi-level transformations and an inner control loop, DTC directly controls the two quantities of interest [6].

A large number of studies have been carried out in order to enhance the operation of DTC-controlled PMSM drives. The main issues that attracted the researchers' attention include torque ripples, non-constant switching frequencies, stator flux oscillations, and current distortion [7].

However, to overcome these drawbacks and maintain the rapid dynamic response nature of DTC, there are many suggested approaches using PI-based controllers, sophisticated PWM methodologies, predictive control approaches, and intelligent optimizing procedures. All these contributions have proved the improvement in the steady state nature and reduced ripples of PMSM drives [8].

2.3.1. Conventional DTC Techniques:

The conventional approach was initially introduced by Takahashi and Noguchi for high-performance AC motor drives This approach involves controlling the flux and electromagnetic torque directly using hysteresis controllers along with an inverter switching table. It has been experimentally observed that this method of DTC is quick in reacting to torque changes and is simpler in construction than other vector-controlled methods [6]. Vas further analyzed the application of DTC in AC drive systems and described the role of flux and torque estimation in achieving direct control of machine variables. The study has stated that the DTC reduces the requirement of coordinate transformations and PWM stages. But the flux estimation errors led to the deterioration of system performance [5].

Krishnan investigated the use of conventional DTC in PMSM drives and found that the technique offers better transient response and quick torque control. The other aspect noted in his research was that the hysteresis-based switching leads to an irregular inverter switching frequency, thereby causing fluctuations in torque in the steady state [2]. There have been many attempts since then to make improvements to traditional DTC techniques through optimization of the switching table and hysteresis band effects. Despite these modifications, however, there were still issues with torque ripple and flux variations [7].

2.3.2. PI Controller-Based DTC Techniques:

To overcome the limitations of conventional DTC systems, several researchers came forward to develop PI controller-based DTC techniques for improving the torque and speed regulation performance in PMSM drives.

One of the main interests of integrating the PI controller in DTC systems was to reduce the torque ripple and improve the steady-state behaviour. It was found that PI controllers help obtain better controlled performance compared to conventional hysteresis-based switching. Different studies applied PI controllers for speed, torque, and flux for improving the stability of the drive and reducing the oscillation in electromagnetic torque [8].

In addition to the above, several optimization methods were suggested for PI controller parameter tuning for DTC drives. These methods enhanced transient response and minimized overshoot during speed changes. Yet, scientists noted that incorrect tuning of controller gains may still influence the performance of the entire drive system [8]. Overall, DTC techniques based on PI controllers showed superior steady-state characteristics and less torque ripple while maintaining the fast dynamic response capability of conventional DTC systems 109].

2.4. Comparative Analysis of Existing Research Work:

Several researchers have compared the performances of the Field Oriented Control (FOC) and Direct Torque Control (DTC) techniques for high-performance PMSM drive applications. The comparative studies were mostly focused on parameters like dynamic response, torque ripple, switching frequency, computational complexity, and steady-state performance. Vas investigated the relative performance of FOC and DTC methods in AC motor drives. It was shown that FOC results in lower torque ripple because of a smooth stator current waveform obtained as a result of decoupled current control using d-q coordinate transformation. On the other hand, the superiority of DTC is due to a fast transient response and ease of implementation as a result of direct control of electromagnetic torque and stator flux [10].

Furthermore, Several comparative studies showed that the proposed advanced DTC techniques exhibit performance characteristics similar to FOC systems and, at the same time, maintain the inherent benefits of direct torque control.

Thus, the present research mainly focuses on developing improved DTC schemes that can combine the fast dynamic response of DTC with the smooth steady-state properties of FOC [5].

Table.3.1: Literature Review of PMSM Drive Control Methods

Author(s)	**Technique/Method**	**Major Contribution**	**Limitation**
Takahashi and Noguchi	Conventional DTC	Fast torque response and simple control structure	High torque ripple
P. Vas	FOC and DTC Comparison	Comparative analysis of FOC and DTC techniques	Variable switching frequency
B. K. Bose	Vector Control FOC	High-performance current control of AC drives	Complex control structure
R. Krishnan	PMSM Drive Modelling	Mathematical modelling of PMSM drives	High computational complexity
Buja and Kazmierkowski	DTC Improvement Techniques	Reduction of torque ripple in DTC drives	Harmonic distortion
Recent Researchers	PI-Based DTC with SVPWM	Improved steady-state performance and reduced torque ripple	Controller tuning complexity

2.5. Conclusion:

This chapter presented a detailed review of the available research works on PMSM drive control techniques, especially on Field Oriented Control and Direct Torque Control Techniques. The Various studies related to conventional FOC, conventional DTC, and PI controller-based DTC techniques were discussed along with their major advantages and limitations. It was observed in the literature review that FOC has good speed regulation, smooth steady-state performance, and accurate speed regulation, whereas DTC has easy implementation and quick dynamic response [4].

From the review of the literature, it can be noted that the FOC scheme offers smooth and accurate steady state response, whereas the Direct Torque Control technique gives fast dynamic response and easy implementation. It was found that conventional direct torque control suffers from high torque ripples as well as variable switching frequency in steady state operation. Different authors have tried to implement improved techniques of DTC in order to overcome the drawbacks of the conventional technique. From the above survey, it may be concluded that more efforts are needed to improve DTC techniques in order to achieve superior performance of PMSM drives [4,8].

Chapter 3

MATHEMATICAL MODELLING OF PMSM MOTOR

3.1. *Introduction:*

The PMSM mathematical model has significant relevance to the study and control of high-performance electric drive systems. Mathematical modelling gives a deeper understanding of how the PMSM behaves under different operational conditions, thereby making advanced control strategies like FOC and DTC more manageable [2]. PMSM drive studies usually involve writing equations in both stationary and rotating coordinate systems. It is more convenient to express three-phase quantities in terms of the d-q reference frame in order to analyze the electromagnetic torque, flux linkages, and dynamic performance. Therefore, the modelling approach presented in this chapter serves as a base for developing and evaluating the performance of the PMSM drive system studied in this work [2],[7]. In this chapter, the mathematical equations that describe PMSM mathematical modelling, reference frame transformation, flux linkage, electromechanical torque, and inverter operation are discussed for the development of the PMSM drive control system [2].

3.2. *Construction and Operating Principle of PMSM:*

PMSM is an AC machine where the magnetic flux density is generated using permanent magnets that are either fitted to or placed inside the rotor body. In contrast to regular synchronous motors, PMSMs lack an excitation winding, hence minimizing losses in the rotor [2]. When compared with ordinary induction motors, PMSMs have advantages such as high efficiencies, smaller sizes, and more power densities because there are no rotor copper losses [2]. Balanced three-phase voltages applied to the stator windings lead to the production of the rotating magnetic field in the air gap. This is because of the magnetic field produced from the permanent magnet in the rotor.

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The interaction between the rotor and the rotating magnetic field of the stator generates the electromagnetic torque. The rotor runs at the same speed as the rotating magnetic field, making the operation of the motor synchronous with the supply frequency [2].

The synchronous speed of PMSM can be expressed as follows [2]:

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$$N_s = \frac{120f}{P} \tag{3.1}$$

where,

N_s : Synchronous Speed (rpm)

f : Supply frequency

P : number of poles

The angular rotor speed is expressed as:

$$\omega_r = \frac{2\pi N_s}{60} \tag{3.2}$$

where,

ω_r = rotor angular speed (rad/s)

The dynamic behaviour of PMSM can be represented by the mechanical motion equation [2]:

$$J\frac{d\omega_r}{dt} = T_e - T_L - B\omega_r \tag{3.3}$$

where,

J : moment of inertia

B : friction coefficient

T_e : electromagnetic torque

T_L : load torque

The PMSMs are usually divided into two categories based on the placement of permanent magnets in the rotor: Surface Mounted PMSM (SPMSM) and Interior PMSM (IPMSM). The reason is that, in SPMSM type motors, the magnets are fixed on the surface of the rotor; therefore, their d-axis and q-axis inductances are almost the same [12].

In SPMSM, $L_d^{'} = L_q^{'}$

However, in IPMSM motors, magnets are embedded into the rotor, which causes rotor saliency [12].

In IPMSM, $L_d^{'} \neq L_q^{'}$

The variation in inductance values significantly affects torque production capability and control characteristics of the motor drive system [12].

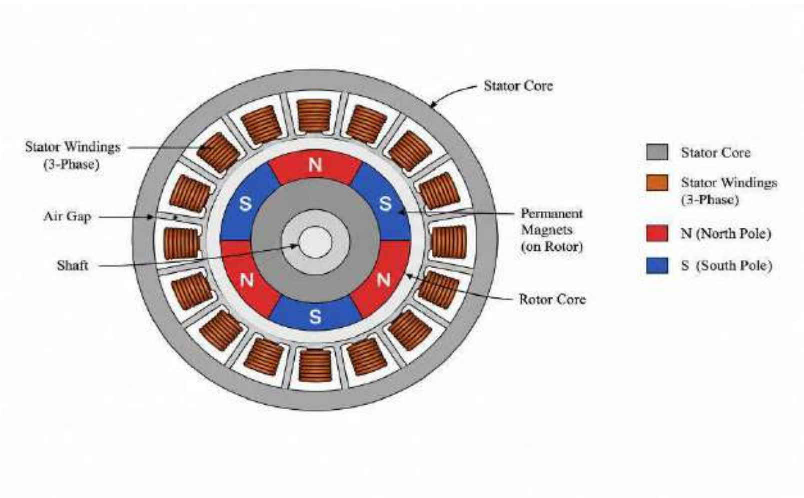

Fig.3.1: Construction of PMSM

3.3. Mathematical Modelling in abc Reference Frame:

The initial representation of the dynamic performance of the PMSM motor is obtained by taking into consideration the voltages, currents, and flux linkages of the stator phase system. This form of modelling is appropriate due to the fact that it takes into account the electrical values that relate to the stator [2]. Even though the abc notation adequately represents the machine operation, it is a relatively complicated system since the electrical quantities continuously change with respect to the rotor position. Therefore, methods of coordinate transformation may be utilized.

16 .The stator voltage equations in the abc reference frame are given by [2]:

$$v_a = r_s i_a + \frac{d\lambda_a}{dt} \tag{3.4}$$

$$v_b = r_s i_b + \frac{d\lambda_b}{dt} \tag{3.5}$$

$$v_c = r_s i_c + \frac{d\lambda_c}{dt} \tag{3.6}$$

19 where,

v_a, v_b, v_c = stator's phase voltages

i_a, i_b, i_c = stator's phase currents

r_s = stator's resistance

$\lambda_a, \lambda_b, \lambda_c$ = stator's flux linkages

The stator flux linkages are represented as [2]:

$$\lambda_a = L_a i_a + \lambda_m \tag{3.7}$$

$$\lambda_b = L_b i_b + \lambda_m \tag{3.8}$$

$$\lambda_c = L_c i_c + \lambda_m \tag{3.9}$$

where,

L_a, L_b, L_c = phase inductances

λ_m = permanent magnet flux linkage

The electromagnetic torque developed by PMSM in abc frame is a function of the interaction between the stator current and rotor magnetic flux. The abc reference frame provides an accurate representation of the motor, but the equations involve time-varying inductances, which increase the complexity of computations for analysis and controller implementation [2].

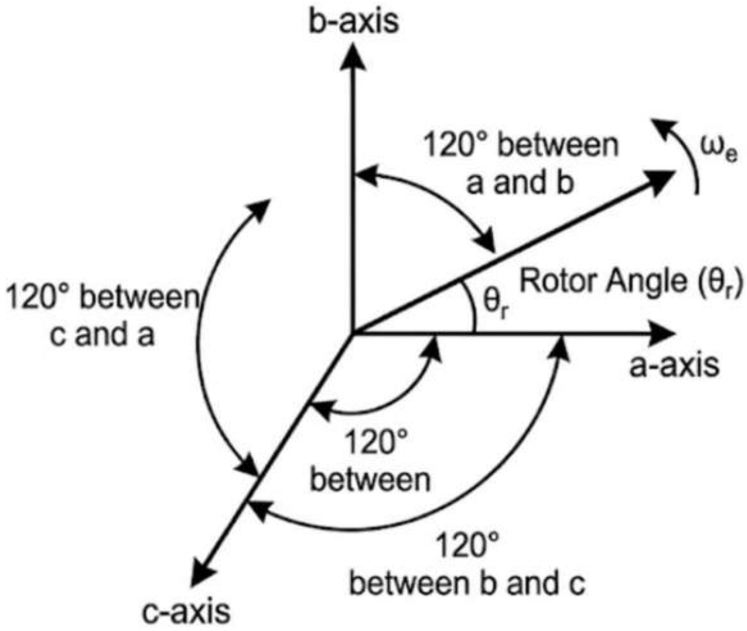

Fig.3.2: Three-Phase abc Reference Frame

3.4. Mathematical Modelling in dq Reference Frame:

To make the study and control of PMSM easy, the three-phase quantities are converted into a reference coordinate system that rotates synchronously. The synchronous reference frame helps to transform the time-varying AC quantities to DC quantities under steady state conditions for easier control system design [3]. In the d-q reference system, the d-axis quantity is related to the magnetic field while the q-axis quantity controls the torque. The decoupling concept makes it possible to control the magnetic field and the torque separately. This is how FOC and DTC work [3],[4].

The dq-axis stator voltage equations of PMSM are expressed as [2]:

$$v_d = r_s i_d + \frac{d\lambda_d}{dt} - \omega_r \lambda_q \tag{3.10}$$

$$v_q = r_s i_q + \frac{d\lambda_q}{dt} + \omega_r \lambda_d \tag{3.11}$$

where,

v_d, v_q = dq-axis voltage

i_d, i_q = dq-axis currents

λ_d, λ_q = dq-axis flux linkages

r_s = stator resistance

ω_r = electrical rotor speed

The dq-axis flux linkage equations are given by [2]:

$$\lambda_d = L_d i_d + \lambda_m \tag{3.12}$$

$$\lambda_q = L_q i_q \tag{3.13}$$

where,

L_d, L_q = d-axis and q-axis inductances

λ_m = permanent magnet flux linkage

3.5. Clarke Transformation:

The Clarke transform transforms three-phase quantities on the stator from the abc reference frame to the stationary α-β reference frame. It decreases the quantity of variables needed for analysis while retaining the necessary electrical information for control purposes [3]. The use of the α-β reference frame is widespread in PMSM control systems as well as being a vital intermediate step in the process of coordinate transformations for motors' control systems.

The transformation from abc frame to αβ frame is represented as [3]:

$$i'_{\alpha} = \frac{2}{3}(i'_{a} - \frac{1}{2}i'_{b} - \frac{1}{2}i'_{c}) \qquad (3.14)$$

$$i'_{\beta} = \frac{2}{3}(\frac{\sqrt{3}}{2}i'_{b} - \frac{\sqrt{3}}{2}i'_{c}) \qquad (3.15)$$

Similarly, the voltage equations in the αβ reference frame are expressed as [3]:

$$v'_{\alpha} = \frac{2}{3}(v'_{a} - \frac{1}{2}v'_{b} - \frac{1}{2}v'_{c}) \qquad (3.16)$$

$$v'_{\beta} = \frac{2}{3}(\frac{\sqrt{3}}{2}v'_{b} - \frac{\sqrt{3}}{2}v'_{c}) \qquad (3.17)$$

3.6. Park Transformation:

The Park Transformation allows for the transformation of stationary α-β coordinates to a d-q rotating frame that is synchronous with the rotor flux. Using this transformation method, the alternating quantities can be transformed into quasi-steady DC quantities. This makes the modeling of machines and design of controllers easy [3]. The transformation provides a means by which individual control of flux and torque producing components of the current may be done. This makes Park Transformation an important tool in Vector Control Drives [3],[4].

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The Park Transformation equations are expressed as [3]:

$$i'_{d} = i'_{\alpha}\cos\theta + i'_{\beta}\sin\theta \qquad (3.18)$$

$$i'_{q} = -i'_{\alpha}\sin\theta + i'_{\beta}\cos\theta \qquad (3.19)$$

Similarly, dq-axis voltages are represented as [3]:

$$v'_{d} = v'_{\alpha}\cos\theta + v'_{\beta}\sin\theta \qquad (3.20)$$

$$v'_{q} = -v'_{\alpha}\sin\theta + v'_{\beta}\cos\theta \qquad (3.21)$$

where,

θ = rotor electrical angle

The inverse Park Transformation is used to convert dq variables back into αβ frame for inverter switching and PWM implementation [3].

$$i_\alpha = i_d \cos\theta - i_q \sin\theta \tag{3.22}$$

$$i_\beta = i_d \sin\theta + i_q \cos\theta \tag{3.23}$$

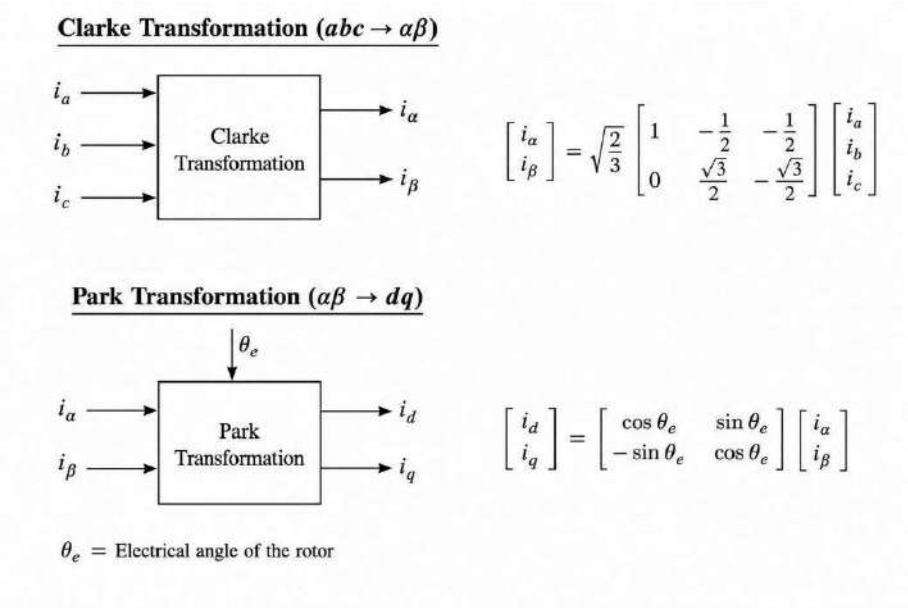

Fig.3.3: Clarke & Park Transformation

3.7. Voltage Source Inverter Model:

The Voltage Source Inverter (VSI) serves as the bridge between the DC source and PMSM drive system. The main role of the VSI is to act as the converter that transforms DC energy into regulated three-phase AC voltages [9]. When the PMSM drive is used, the control of the inverter depends on the chosen control method. Switching components like IGBTs or MOSFETs can be employed to create voltage waveforms. The resulting switching patterns have an impact on motor performance, torque production, and current quality [9]. A typical three-phase VSI has six switching elements in three inverter legs. Proper combination of the switching modes creates voltage vectors for the implementation of the FOC and DTC control methods.

The inverter output phase voltages are represented as [9]:

$$V_a = \frac{V_{dc}}{2}(S_a - S_a') \tag{3.24}$$

$$V_b = \frac{V_{dc}}{2}(S_b - S_b') \tag{3.25}$$

$$V_c = \frac{V_{dc}}{2}(S_c - S_c') \tag{3.26}$$

where,

V_{dc} = DC link voltage

S_a, S_b, S_c = upper switch states

S_a', S_b', S_c' = lower switch states

Inverter switching states dictate the output voltage vector fed to the PMSM drives. Inverter control forms an integral part of FOC and DTC methods used in controlling the rotor speed, torque, and stator flux. [9].

3.8. Conclusion:

In this chapter, mathematical modeling of the Permanent Magnet Synchronous Motor was presented in both abc and d-q frames. The structure, operation, voltage equations, flux linkages equations, Clarke transform, Park transform, and inverter were explained. The transformation of the three-phase quantities to orthogonal frames makes it easier to analyse the PMSM. The derived mathematical model is the basis for the implementation of field-oriented control and direct torque control using proportional-integral space vector pulse width modulation explained in the upcoming chapters.

Chapter 4

DIRECT TORQUE CONTROL

4.1. Introduction:

Direct Torque Control (DTC) has been considered an efficient way of controlling PMSM drive systems due to the ability to regulate torque quickly and because of the relative simplicity of the control scheme. In contrast to control algorithms based on vector control concepts, DTC is able to directly regulate the electromagnetic torque and stator flux without utilizing numerous current control loops or transformations [5], [6]. The DTC algorithm calculates torque and flux in real-time and chooses suitable inverter switching modes depending on the state of the drive system. The use of such a scheme helps improve the dynamic performance of DTC control; nevertheless, it usually suffers from torque ripple, flux oscillations, and fluctuating switching frequency in the steady-state mode [7]. This chapter presents the operating principle of conventional DTC, voltage vector selection, switching-table implementation, and the modifications introduced through PI-controller and SVPWM-based techniques for performance enhancement.

4.2. Conventional Direct Torque Control of PMSM:

4.2.1. Principle of Conventional DTC:

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Conventional Direct Torque Control uses the principle of direct stator flux and electromagnetic torque control via proper switching actions of the inverter. Motor variables are constantly estimated based on measurements of stator voltage and current values, which are then compared to their respective reference values [6]. The resultant torque and flux deviations are filtered out by hysteresis comparators. Based on the outcome of the comparators and the present position of the stator flux vector, the proper inverter switching state is chosen from the list of available switching states [6], [7].

The stator flux linkage components in the stationary αβ reference frame are expressed as [5]:

$$\lambda_\alpha = \int (V_\alpha - R_s i_\alpha) dt \tag{4.1}$$

$$\lambda_\beta = \int (V_\beta - R_s i_\beta) dt \tag{4.2}$$

The magnitude of stator flux linkage is given by [5]:

$$\lambda_s = \sqrt{(\lambda_\alpha^2 + \lambda_\beta^2)} \tag{4.3}$$

where,

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$\lambda_\alpha, \lambda_\beta$ = stator flux components

V_α, V_β = stator voltage components

i_α, i_β = stator current components

R_s = stator resistance

The electromagnetic torque is estimated using the flux and current components as [6]:

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_\alpha i_\beta - \lambda_\beta i_\alpha) \tag{4.4}$$

where,

T_e = electromagnetic torque

P = number of poles

The position of the stator flux vector is determined from the flux angle:

$$\theta_s = \tan^{-1}\left(\frac{\lambda_\beta}{\lambda_\alpha}\right) \tag{4.5}$$

The estimated values for the torque and flux are continuously monitored against the corresponding reference values using hysteresis controllers. Inverting states are selected based on the output obtained from the hysteresis comparators and also the sector in which the stator flux vector falls.

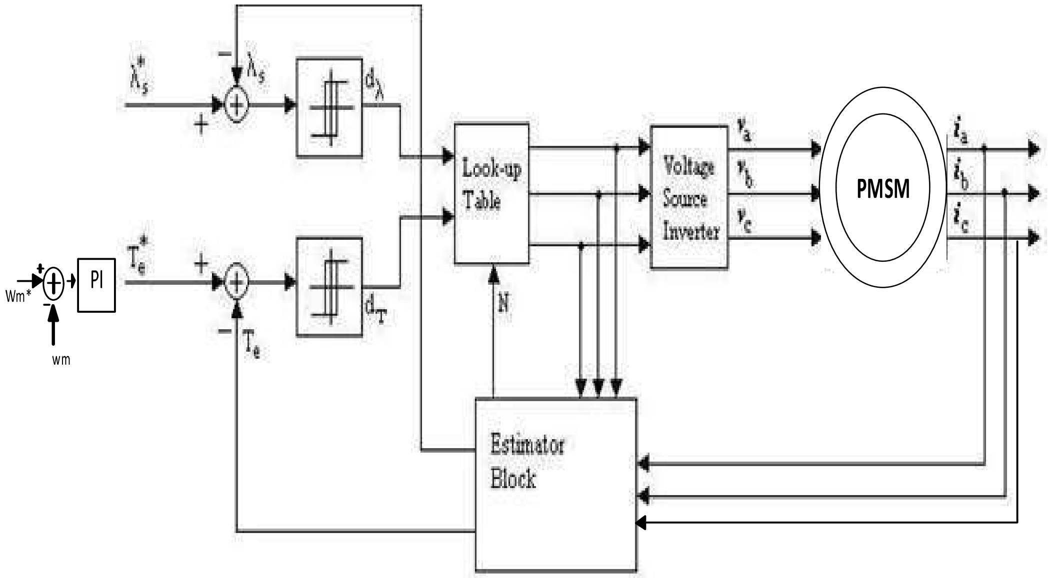

Fig.4.1: Block Diagram of Conventional DTC

4.2.2. Switching Table and Voltage Vector Selection:

In conventional DTC drive schemes, the inverter voltage vectors are selected using a switching table that is predetermined by the controller. Selection of voltage vectors is dependent on the error of torque, error of flux, and position of the stator flux vector in the instantaneous αβ coordinate system [6]. Stator flux vector covers six sectors in the stationary reference frame, and based on the sector in which the machine operates and control requirements, a suitable voltage vector can be chosen to increase or reduce electromagnetic torque and stator flux.

The inverter output voltage vectors are represented as:

$$V_s = \frac{2}{3} V_{dc} (S_a + \alpha S_b + \alpha^2 S_c) \tag{4.6}$$

where,

V_{dc} = DC link voltage

S_a, S_b, S_c = inverter switching states

$a = e^{\frac{j2\pi}{3}}$

The stator flux sector is determined from the flux angle:

$$\theta_s = \tan^{-1}(\frac{\lambda_\beta}{\lambda_\alpha}) \tag{4.7}$$

The voltage-source inverter is composed of two levels which produce six active voltage vectors and two zero vectors. Active vectors are used for altering the amplitude and placement of the flux vector on the stator side, while zero vectors are normally used for maintaining the same operation without any additional switch operations [5].

In conventional DTC, the inverter switching table selects appropriate voltage vectors according to:

- torque error
- flux error
- stator flux sector position

The active voltage vectors v_1 to v_6 are used for increasing or decreasing electromagnetic torque and stator flux, whereas zero voltage vectors v_0 and v_7 They are generally used to maintain the current flux condition.

Table.4.1: Switching Table for Conventional DTC

$d\lambda$	dT_e	n=1	n=2	n=3	n=4	n=5	n=6
1	1	v_2	v_3	v_4	v_5	v_6	v_1
	0	v_7	v_0	v_7	v_0	v_7	v_0
	-1	v_6	v_1	v_2	v_3	v_4	v_5
0	1	v_3	v_4	v_5	v_6	v_1	v_2
	0	v_0	v_7	v_0	v_7	v_0	v_7
	-1	v_5	v_6	v_1	v_2	v_3	v_4

4.2.3. Limitations of Conventional DTC:

Despite its advantages of high transient response speed and simplicity in the implementation process, conventional DTC has a number of drawbacks that hinder its steady-state performance. Due to the application of hysteresis controllers, inverter switching frequencies change over time, thus producing undesirable torque ripples and flux oscillations [7].

Moreover, abrupt switching processes are liable to generate distortions of currents in the motor drive circuit, especially during the period when motor works at low speed. Thus, there are a great many modified versions of DTC algorithms that have been developed in an effort to achieve steady-state performance improvement without compromising dynamic performance [15].

4.3. PI Controller-Based DTC:

4.3.1. Role of PI Controller in DTC:

PI controllers are used in order to improve the performance of the steady-state operation of the classical direct torque control system. The role of using the PI controller is that of improving the torque ripple, regulating the speed of operation, as well as improving flux control accuracy [8]. This controller will provide corrections for the control signals by considering the difference between the measured and reference quantities. This will result in smooth operation after appropriate tuning of the controller gain [8].

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The speed controller generates the reference torque component based on the error between the reference speed and actual motor speed. The error signal is represented as:

$$e(t) = \omega_r^* - \omega_r \tag{4.8}$$

The output of the PI controller is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{4.9}$$

where:

K_p = proportional gain

K_i = integral gain

$e(t)$ = speed error

The proportional term improves transient response, whereas the integral term reduces steady-state error.

4.3.2. PI-Based Torque and Flux Control:

Within the proposed control strategy, PI controllers are used for controlling the torque and flux signals in place of the traditional hysteresis comparator approach. The change facilitates more gradual control and mitigates the sharp transitions that take place in DTC systems. The controller signals will then be obtained through a process of comparing the error of torque and flux, followed by an assessment for the necessary voltage vector values. Improved torque control is made possible in such a way.

The use of PI controllers produces smoother control signals and minimizes abrupt switching actions.

The torque error is represented as:

$$e_T = T_e^* - T_e \tag{4.10}$$

Similarly, the flux error is given by:

$$e_\lambda = \lambda_s^* - \lambda_s \tag{4.11}$$

The corresponding PI controller outputs are represented as:

$$u_T = K_p e_T + K_i \int e_T dt \tag{4.12}$$

$$u_\lambda = K_p e_\lambda + K_i \int e_\lambda dt \tag{4.13}$$

The controller outputs are further utilized for generating appropriate inverter switching signals through SVPWM.

4.3.3. SVPWM-Based Switching Technique:

SVPWM is integrated within the DTC scheme in order to ensure constant switching frequency and effective voltage vector synthesis. Unlike traditional methods based on switching tables, the reference voltage vector synthesis by SVPWM is accomplished using active and zero vectors in an optimized manner [9]. The reference voltage is determined based on the torque and flux controllers and then converted into the stationary frame for generating switching signals for the inverter. Using SVPWM allows for considerable reduction of torque ripple and better voltage utilization [9], [19].

The reference voltage vector in αβ reference frame is represented as:

$$V_{ref} = V_\alpha + jV_\beta \tag{4.14}$$

The magnitude of the reference voltage vector is expressed as:

$$\left|V_{ref}\right| = \sqrt{(V_\alpha^2 + V_\beta^2)} \tag{4.15}$$

The angle of the reference voltage vector is calculated as:

$$\theta = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \tag{4.16}$$

In SVPWM, the inverter switching states are represented as voltage vectors in the stationary αβ plane. A two-level inverter generates six active voltage vectors and two zero voltage vectors, forming a hexagonal structure.

Integration of SVPWM in the proposed DTC system enhances the utilization of voltage by the inverter and generates a smooth transition of voltage. As a result, electromagnetic torque ripple, stator flux oscillations, and harmonic distortion become less compared to traditional DTC methods [19].

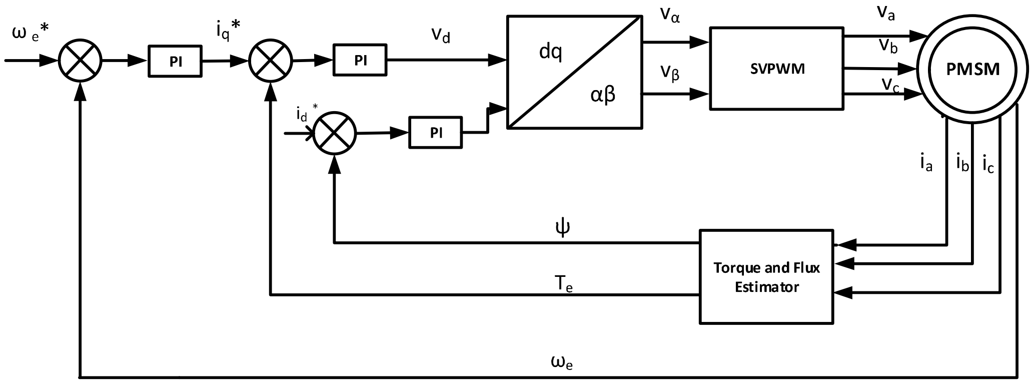

Fig.4.2: PI-Based DTC Control Algorithm

4.4. Conclusion:

In this chapter, the operating principles of standard Direct Torque Control and improvements brought about by the application of PI controller and SVPWM have been explained. Standard DTC can give fast torque dynamics and has a simple control algorithm, but its operation is hampered by torque ripple, flux ripples, and varying switching frequencies at steady state [6],[7]. These drawbacks were overcome by the application of PI controllers to ensure accurate control and minimize ripples, as well as the utilization of SVPWM for constant switching frequency voltage vector generation. This control technique will be simulated in the following chapters.

Chapter 5

FIELD ORIENTED CONTROL

5.1. Introduction:

Field-Oriented Control (FOC) is one of the most widely adopted controlmethods in the drives of PMSM motors, due to its ability to accurately regulate torque and speed. This allows AC motors to behave in the way similar to separate excited DC motors thanks to an independent control of their flux and torque components [3], [4]. Coordinate transformations are used as part of the field-oriented control, which transform three-phase stator quantities into a synchronously rotating frame of references d-q. Due to this control technique, the variables of the motor can be independently regulated, increasing their dynamic and static performance [4]. The field-oriented control is applied along with the PI controllers and SVPWM in the PMSM motor drives. Voltage utilization, harmonic reduction, and efficient operation of the motor under different loads are achieved through their use [9]. This chapter presents the operating principle, mathematical representation, current-control strategy, and PI-controller implementation used in the FOC-based PMSM drive system.

5.2. Principle of Field-Oriented Control:

FOC works on the basis of the conversion of three-phase currents in the stator to a rotating reference frame coinciding with the rotor's magnetic field. The conversion allows for independent control of the current components responsible for the generation of the flux and torque respectively [4]. In the rotating reference frame, the d-axis current controls the flux, while the q-axis current regulates the electromechanical torque of the system. Decoupled control is important in simplifying the control of the PMSM and enhancing its performance [3]. The conversion usually employs Clarke and Park transformations that convert three-phase quantities to orthogonal components for the purpose of control.

The Clarke Transformation converts three-phase currents into stationary αβ reference frame:

$$i_\alpha = \frac{2}{3}(i_a - \frac{1}{2}i_b - \frac{1}{2}i_c) \tag{5.1}$$

$$i_\beta = \frac{2}{3}(\frac{\sqrt{3}}{2}i_b - \frac{\sqrt{3}}{2}i_c) \tag{5.2}$$

The stationary αβ components are transformed into rotating dq reference frame using Park Transformation:

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta \tag{5.3}$$

$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \tag{5.4}$$

The electromagnetic torque equation of PMSM is expressed as:

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_m i_q \tag{5.5}$$

The torque expression indicates that electromagnetic torque is primarily influenced by the q-axis current component. Consequently, accurate regulation of the q-axis current enables effective torque control, whereas the d-axis component is used for flux regulation.

5.3. dq Axis Current Control in FOC:

In drives for PMSMs with a FOC, the currents in the stator are modeled in a synchronously rotating coordinate system which allows independent control of d-axis and q-axis current components. This decoupling makes control easier [3]. d-axis current is normally kept as zero or near-zero in the case of surface-mounted PMSMs, since this helps in efficient energy consumption. The control of q-axis current depends on the torque demanded by the load [2],[7]. Independent control of the currents makes the performance better in terms of dynamic behavior and speed control.

The dq-axis voltage equations of PMSM are expressed as [2]:

$$V_d = R_s i_d + L_d \frac{d\lambda_d}{dt} - \omega_r L_q i_q \tag{5.6}$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r (L_d i_d + \lambda_m) \tag{5.7}$$

For Surface Mounted PMSM, the d-axis reference current is generally maintained at zero [7]:

$$i_d^* = 0 \tag{5.8}$$

This condition eliminates unnecessary flux-producing current and improves motor efficiency. Under this operating condition, the electromagnetic torque becomes directly proportional to the q-axis current [5].

The electromagnetic torque equation is represented as [7]:

$$T_e = \frac{3}{2}\frac{P}{2}\lambda_m i_q \tag{5.9}$$

The choice of d-axis current for surface-mounted PMSMs is typically made as zero. This mode of operation makes the generation of electromagnetic torque solely dependent on the q-axis current.

The dq-axis current control structure improves decoupling between torque and flux components and provides smoother steady-state performance compared to conventional control techniques.

5.4. PI Controller-Based FOC:

Proportional-Integral (PI) controllers have been widely used in PMSM drives based on Field Oriented Control due to their simplicity in design and good control performance. The function of such controllers is the control of motor speed and current variables in accordance with their reference values [3]. A speed controller is the block which provides the q-axis current reference necessary to maintain the required motor speed. The blocks of d- and q-axis currents control voltage references for inverter [10].

The speed controller compares the reference speed with the actual rotor speed to generate the speed error:

$$e(t) = \omega_r^* - \omega_r \tag{5.10}$$

Where,

ω_r^* = reference speed

ω_r = actual motor speed

The output of the PI controller is represented as:

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{5.11}$$

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The speed control loop generates an error signal which is derived from the difference between the reference speed and the actual speed. The error signal is used in conjunction with the PI controller to obtain the necessary command signal for generating the torque generating current..

The output of the speed PI controller generates the reference q-axis current:

$$i_q^* = K_p e(t) + K_i \int e(t)dt \tag{5.12}$$

15

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The generated reference current is compared with the actual q-axis current, and the error is fed to the current PI controllers to generate appropriate control voltages. Similarly, the flux-producing current is controlled by the d-axis current controller. For Surface PMSM drives, the reference d-axis current is generally kept at zero for maximum torque per ampere operation.

The use of PI controllers in FOC provides smooth speed regulation, reduced steady-state oscillations, and improved current waveform quality under varying load conditions. The smooth control action of PI controllers minimizes current oscillations and enhances overall drive efficiency [10]. Therefore, FOC remains one of the most reliable and widely adopted control techniques for high-performance PMSM drive applications.

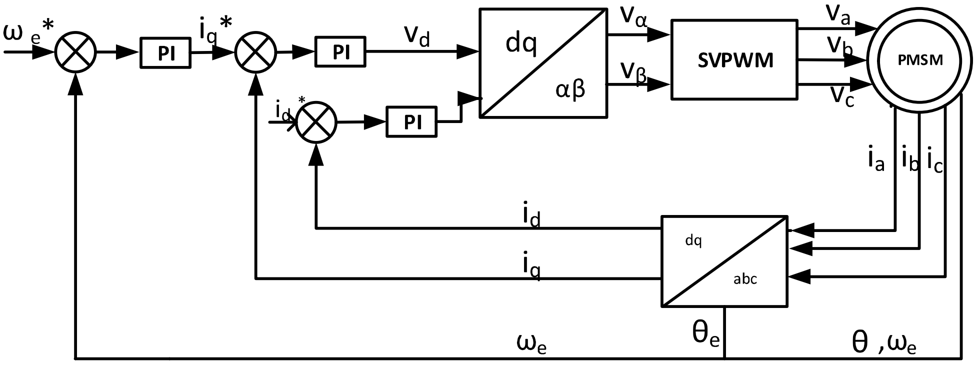

Fig.5.1: Block Diagram of FOC

5.5. Conclusion:

In this chapter, FOC technique was explained in this chapter, which can be used in PM synchronous motors drives. Operating procedure, coordinate transformation, dq axes currents, and the concept of PI controller was covered. FOC allows controlling each magnetic field separately to obtain better speed and stable operation of the motor. Application of PI controllers improves transient response and decreases steady state error, whereas the use of SVPWM makes more efficient use of inverters [9]. The FOC model built is taken as the baseline strategy against which we compare the suggested DTC based on PI-SVPWM in further simulations.

Chapter 6

Results and Discussion

6.1. Introduction:

This chapter presents simulation results for Field Oriented Control (FOC) and the proposed PI-SVPWM-based Direct Torque Control (DTC) techniques for the PMSM drive system using MATLAB/Simulink environment. Both FOC and proposed PI-SVPWM-based DTC techniques were implemented with the same motor parameters and operating conditions to evaluate the performance properly. In addition, the effectiveness of the developed control strategy is evaluated by performing a comparative analysis between the FOC and the proposed DTC methods. The simulation results obtained show the improvement achieved in the proposed PI-SVPWM-based DTC method for PMSM drive applications.

6.2. Simulation Parameters:

Table 6.1: Parameters of the PMSM

Parameter	Symbol	Values
Stator resistance	R_s	0.901 Ω
Inductance	$L_d = L_q$	6.552 mH
No of pole pairs	P	4
PM flux linkage	λ	0.09427 Wb
Rated Current	I_{rated}	4.2 A
Rated Power	P_{rated}	0.75 kW
Rated Torque	T_{rated}	2.4 N-m
Rated speed	ω_m	3000 r/min
DC-bus Volatge	V_{dc}	220 V
Inertia	J	1.2 $kg.m^2.10^{-4}$

6.3. DTC Result:

6.3.1. Rated Load Condition:

The performance of DTC for the PMSM drive system is analyzed using MATLAB/Simulink under rated load condition. Initially, the motor operates under no load, and at $t = 0.2\ sec$, the rated load torque $(T_L = 2.4\ Nm)$is applied. Fig. 6.1 shows the speed, electromagnetic torque, and stator flux responses of the PMSM drive system.

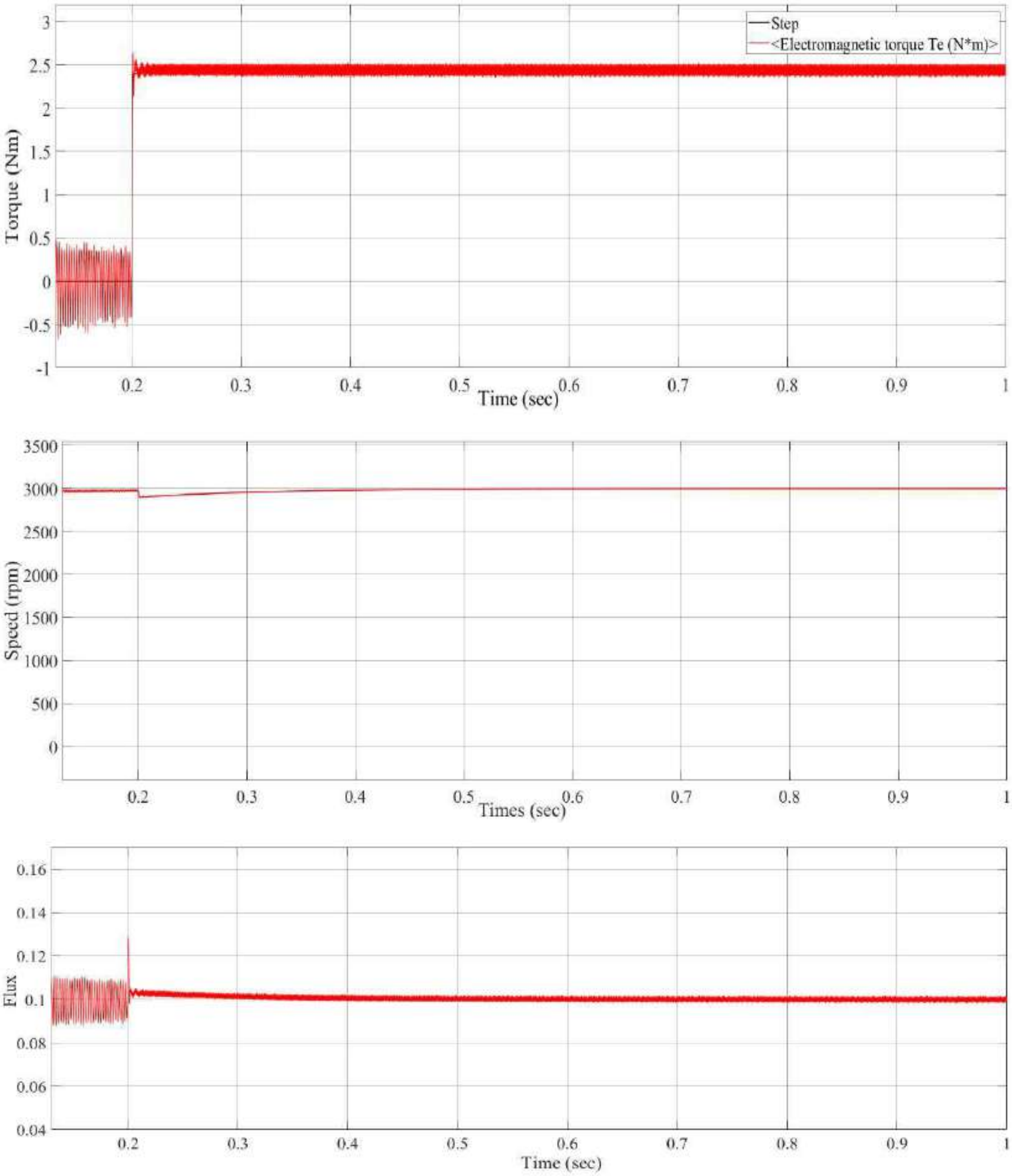

Fig.6.1: Response of torque, speed, and flux of DTC at rated load condition

6.3.2. Variable Load Conditions:

The performance of DTC for the PMSM drive system is analyzed using MATLAB/Simulink under varying load conditions. Initially, the motor operates under a no-load condition. At $t = 0.2\ sec$, a load torque of $T_L = 0.6\ Nm$is applied, followed by a half-load condition $(T_L = 1.2\ Nm)$and finally the rated load condition $(T_L = 2.4\ Nm)$. Fig. 6.2 shows the speed, electromagnetic torque, and stator flux responses of the PMSM drive system under varying load conditions. The motor tracks the reference torque smoothly.

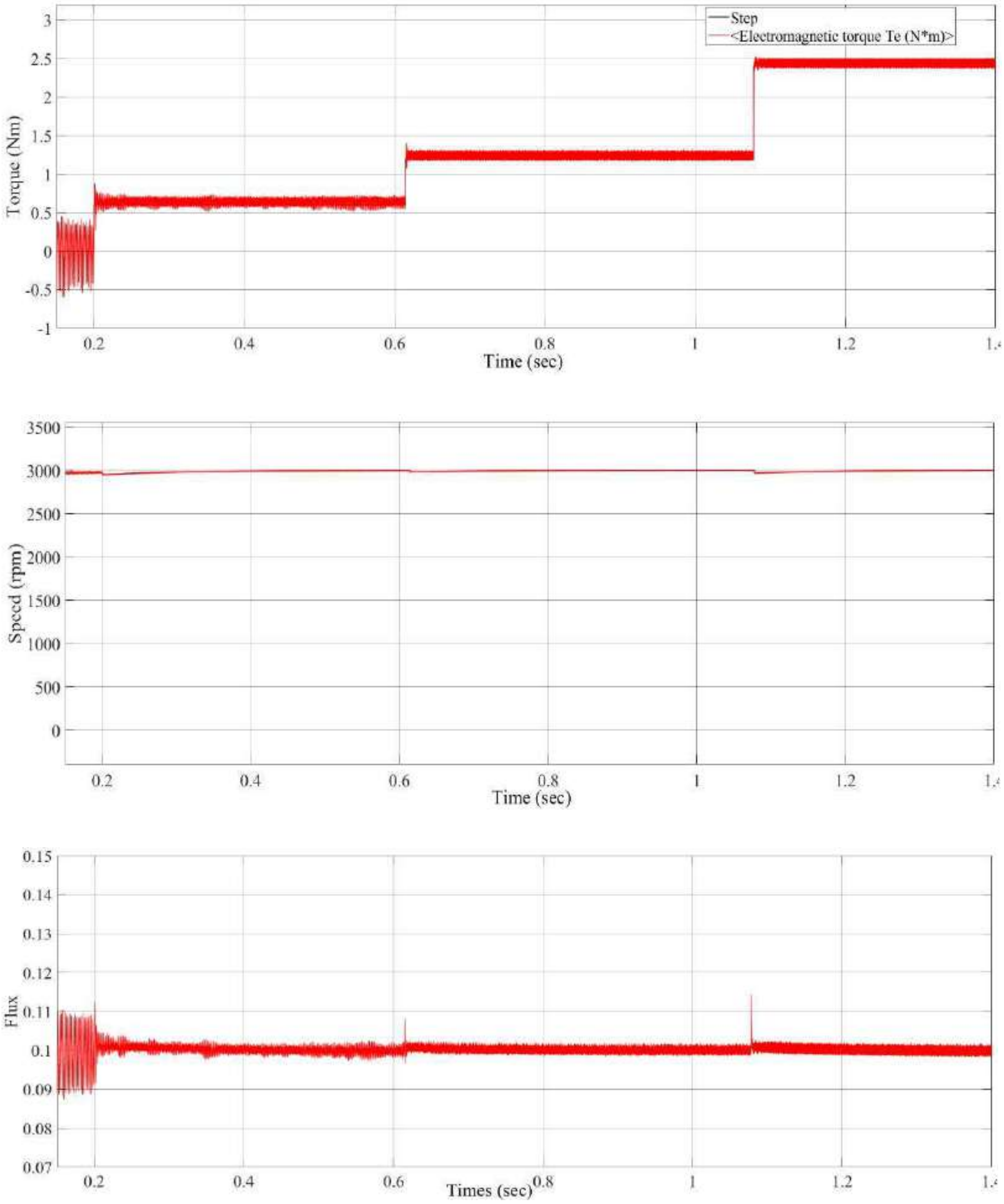

Fig.6.2: Response of torque, speed, and flux of DTC at variable load conditions

6.4.FOC Result:

6.4.1. Rated Load Condition:

The performance of Field Oriented Control (FOC) for the PMSM drive system is analyzed using MATLAB/Simulink under rated load condition. Initially, the motor operates under no-load condition, and at $t = 0.2\, sec$, the rated load torque $(T_L = 2.4\, Nm)$is applied. Fig. 6.3 shows the speed and electromagnetic torque responses of the PMSM drive system.

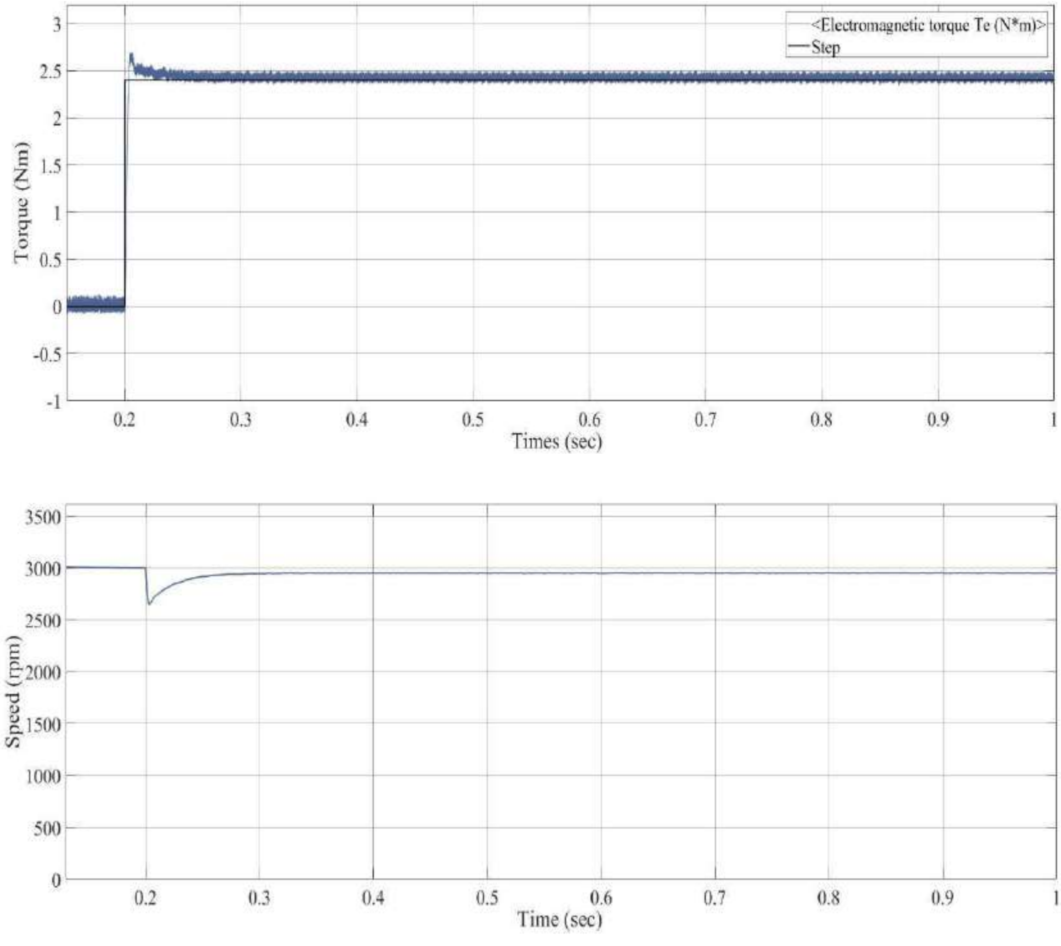

Fig.6.3: Response of torque and speed of FOC at rated load condition

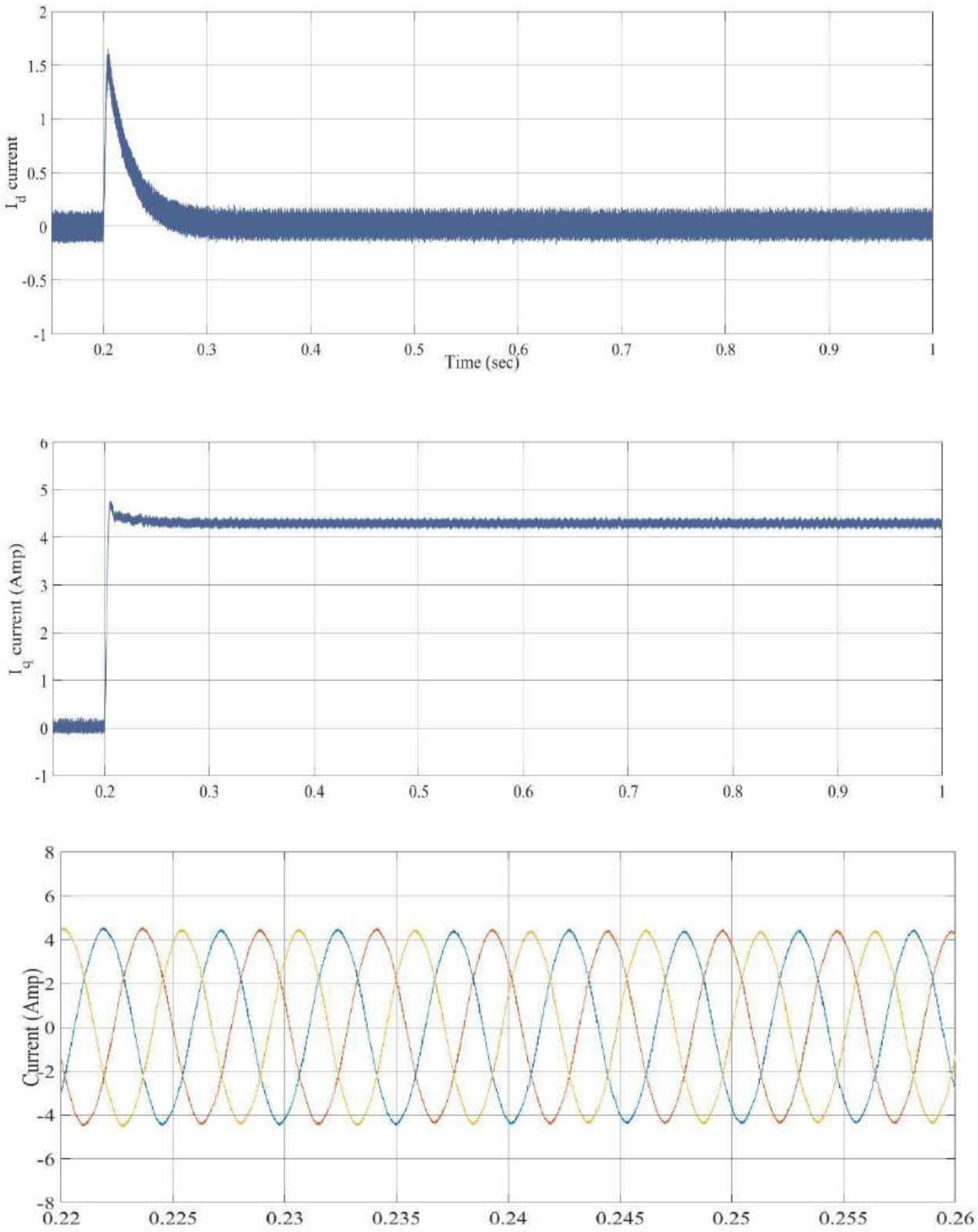

Fig.6.4: Response of I_d , I_q and stator current of FOC at the rated load condition

6.4.2. Variable Load Condition:

The performance of FOC for the PMSM drive system is analyzed using MATLAB/Simulink under varying load conditions. Initially, the motor operates under no-load condition. At $t = 0.2\ sec$, a load torque of $T_L = 0.6\ Nm$is applied, followed by half-load condition $(T_L = 1.2\ Nm)$and finally the rated load condition $(T_L = 2.4\ Nm)$. Fig. 6.5 shows the speed, electromagnetic torque, and stator flux responses of the PMSM drive system under varying load conditions.

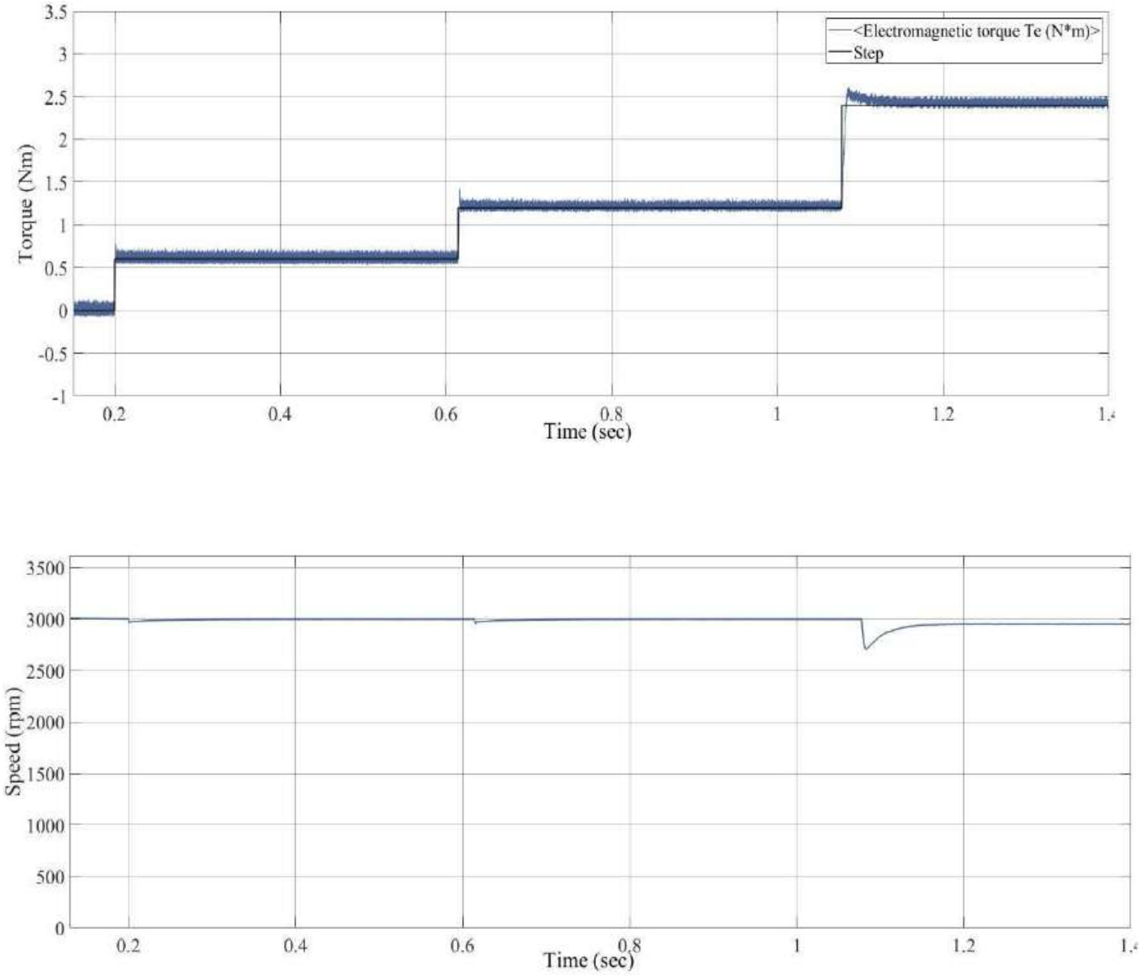

Fig.6.5: Response of torque and speed of FOC at variable load conditions

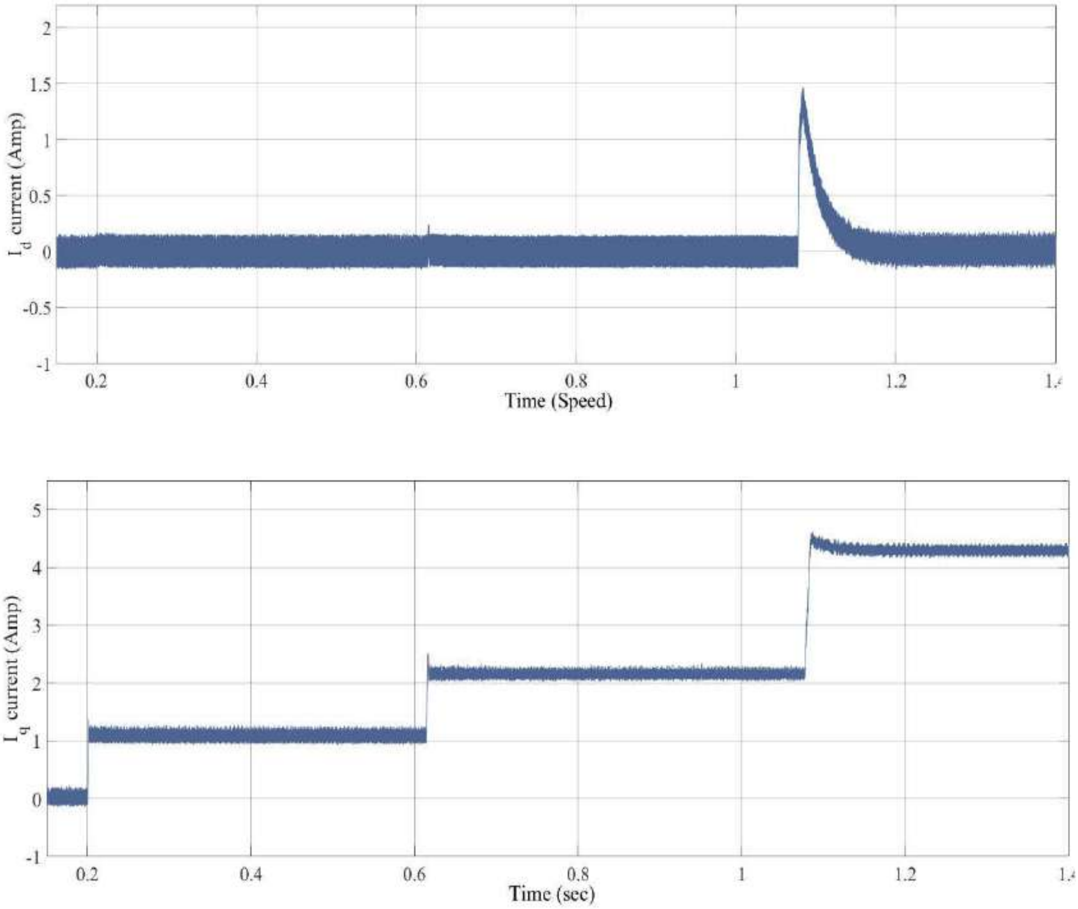

Fig.6.6: Response of I_d and I_qCurrent of FOC at variable load conditions

6.5. Comparative Analysis of FOC and DTC:

A comparative analysis between FOC and DTC is carried out under identical operating conditions in order to evaluate the dynamic and steady-state performance of the PMSM drive system. Initially, the motor operates under no-load condition, and at $t = 0.2\ sec$, the rated load torque $(T_L = 2.4\ Nm)$is applied to both control techniques. The comparative results show that the conventional DTC technique provides faster transient response and reaches steady-state more quickly than FOC during load transition. However, the torque response of FOC exhibits comparatively lower ripple during steady-state operation because of thesmooth dq-axis current regulation and PI controller action. Fig. 6.7 shows the comparative speed and electromagnetic torque responses of FOC and DTC techniques under load transition condition.

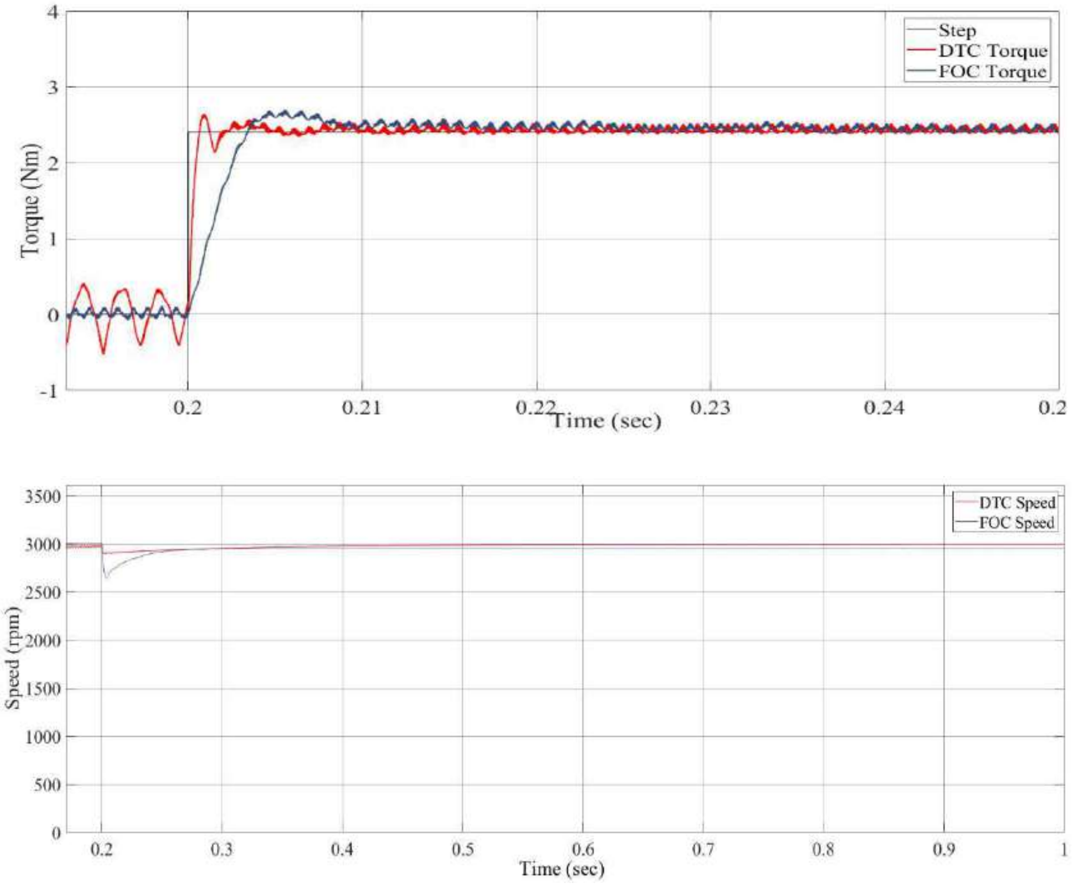

Fig.6.7: Comparative speed and torque responses of FOC and DTC during the no-load to rated-load transition.

Table.6.2: Comparison of Torque Response Characteristics of FOC and DTC Controlled PMSM

Parameter	**DTC**	**FOC**
Rise Time	0.001 sec	0.004 sec
Settling Time	0.205 sec	0.214 sec
Peak Overshoot	12%	10.2%
peak-to-peak ripple	0.165	0.1442

6.6. Discussion:

From the obtained simulation results, it is observed that both FOC and conventional DTC techniques provide satisfactory speed regulation capability for PMSM drive applications. During sudden load application at $t = 0.2\, sec$, the conventional DTC technique responds more rapidly because of direct control of electromagnetic torque and stator flux without involving complex coordinate transformations. Due to this reason, DTC achieves faster transient response compared to FOC.

On the other hand, the FOC technique provides smoother electromagnetic torque response and reduced steady-state torque ripple because of decoupled dq-axis current control and PI controller-based regulation. The torque waveform obtained using FOC appears more stable during steady-state operation, whereas conventional DTC exhibits noticeable torque oscillations due to hysteresis-based switching operation and variable switching frequency.

Therefore, it can be concluded that conventional DTC is more suitable for applications requiring fast dynamic response, while FOC provides superior steady-state performance and lower torque ripple characteristics for PMSM drive systems [20].

Chapter 7

CONCLUSIONS AND FUTURE SCOPE

7.1. Conclusion:

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This thesis proposed a comparative study of Field Oriented Control (FOC) and PI-SVPWM-based Direct Torque Control (DTC) techniques for a Permanent Magnet Synchronous Motor (PMSM) drive system. In this work, different control strategies and mathematical modelling of PMSM were developed and implemented in MATLAB/Simulink environment for performance evaluation under identical operating conditions. The conventional DTC was analyzed and its main drawbacks, such as high torque ripple, flux ripple, and variable switching frequency, were identified. To overcome these drawbacks, a PI controller and Space Vector Pulse Width Modulation (SVPWM) technique were combined with a DTC structure. The proposed PI-SVPWM-based DTC method enhanced the steady-state and transient performance of the PMSM drive system. The simulation results demonstrated that the proposed DTC technique achieved reduced torque ripple, improved speed response, and better flux regulation compared to the conventional DTC method.

Also, a comparison has been done between FOC and proposed DTC using speed, torque, current and flux waveforms. The results obtained proved that the proposed PI-SVPWM-based DTC technique provides an effective solution for high-performance PMSM drive applications. The overall study confirms that the combination of PI controller and SVPWM with DTC significantly improves the performance of the PMSM drive system under various operating conditions.

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7.2 Future Scope:

The present work can be extended in several directions to improve the performance and practical implementation of PMSM drive systems. The proposed PI-SVPWM-based DTC technique may be implemented in real-time

hardware platforms like DSP, FPGA, or dSPACE systems for experimental validation. Other advanced intelligent optimization techniques like Fuzzy Logic Control, Artificial Neural Network (ANN), Genetic Algorithm (GA), and Adaptive Control techniques can also be combined with DTC and FOC techniques for automatic controller tuning and further ripple reduction.

The sensorless PMSM drive operation can be studied in future work to lower the system cost and enhance the reliability. In addition, the advanced modulation techniques and multilevel inverter topology can reduce the harmonic distortion and improve the power quality. The proposed control strategy can also be extended to electric vehicle drives, renewable energy systems, robotics and high-performance industrial applications requiring fast dynamic response and efficient motor operation.

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