

FUZZY SLIDING MODE SPEED CONTROLLER WITH ACTIVE DAMPING CONTROL FOR DUAL-PMSM

A PROJECT REPORT

submitted by

SHAHINA S

(Reg. No. TKM20EEII17)

to

the APJ Abdul Kalam Technological University
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology

in

Electrical and Electronics Engineering

with specialisation in

Industrial Instrumentation and Control



Department of Electrical and Electronics Engineering

TKM College of Engineering

Kollam - 691005

KERALA

JULY 2022

DECLARATION

I undersigned hereby declare that the project report entitled "**Fuzzy Sliding Mode Speed Controller With Active Damping Control for Dual-PMSM**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of *Prof. Farsana Muhammed*, Assistant Professor, Department of Electrical and Electronics Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Kollam
July 01, 2022

SHAHINA S

**DEPARTMENT OF ELECTRICAL AND ELECTRONICS
ENGINEERING
TKM COLLEGE OF ENGINEERING
KOLLAM - 691005**



CERTIFICATE

This is to certify that the report entitled " **Fuzzy Sliding Mode Speed Controller With Active Damping Control for Dual-PMSM** " submitted by **SHAHINA S , (Reg. No. TKM20EEII17)** of fourth semester to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, is a bonafide record of the project work done by her under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

Prof. Farsana Muhammed
Project Supervisor
Assistant Professor
Department of EEE
TKM College of Engineering

Prof. Sumayya Jaleel
Project Coordinator
Assistant Professor
Department of EEE
TKM College of Engineering

Prof. Shanavas T N
PG Coordinator
Associate Professor
Department of EEE
TKM College of Engineering

Dr. Sabeena Beevi K
Head of the Department
Associate Professor
Department of EEE
TKM College of Engineering

Acknowledgement

A lot of effort and hard work has been put into this project in course of its presentation. However, it would not have been possible without the kind support and help of many individuals and other sources. I would like to extend my sincere thanks to all of them. I take this opportunity to express my deep sense of gratitude and sincere thanks to all who helped me to complete this project report successfully.

I express my sincere thanks to *Dr. T A Shahul Hameed*, Principal, TKM College of Engineering for his encouragement in the completion of my project.

I thank *Dr. Sabeena Beevi K*, Head of the Department, Department of Electrical and Electronics Engineering, *Dr. Imthias Ahamad T P*, Professor, TKM College of Engineering and *Prof. Shanavas T N*, PG Coordinator, Department of Electrical and Electronics Engineering for their support and cooperation.

I am greatly thankful to my Project Supervisor *Prof. Farsana Muhammed*, Assistant Professor, Department of Electrical and Electronics Engineering for her supervision, assistance and helpful suggestions.

I am deeply indebted to *Prof. Sumayya Jaleel*, Assistant Professor, Project Coordinator, Department of Electrical and Electronics Engineering and *Prof. Amal A*, Assistant Professor, Department of Electrical and Electronics Engineering, for their excellent guidance, positive criticism and valuable comments.

Finally I thank my parents, friends, near and dear ones who directly and indirectly contributed to the successful completion of my project.

SHAHINA S

Abstract

Permanent magnet synchronous motors (PMSM) are extensively used in many industrial applications such as electric train tractions, industrial robots, etc. due to their high torque to weight ratio, high power density, high efficiency, reliability, and ease of maintenance. When compared to single PMSM, the dual PMSM is more cost effective. In the proposed system the two motors are operated in a master/slave control scheme. When the load torque is varied, there is an oscillation occurred in the slave motor. In this work, active damping control is designed to suppress this unwanted oscillations. From the analysis of the system model, it is inferred that a small variation in motor parameters leads to a large variation in system performance. So various speed control techniques with active damping control are designed by using different controllers (PI, FUZZY, SMC, FUZZY-SMC) to improve the system performance. A comparison of the performance of different controllers with and without parameter variations is evaluated in MATLAB/Simulink. By comparing the results, it is inferred that the Fuzzy Sliding Mode Controller gives the best performance among PI, FUZZY and SMC.

Contents

Abstract

List of Tables **i**

List of Figures **ii**

Abbreviations **iv**

Notations **v**

1 INTRODUCTION **1**

1.1 General Background 1

1.2 Problem Definition 2

1.3 Objectives 2

1.4 Organisation of the Report 3

2 LITERATURE REVIEW **4**

2.1 Overview 4

2.2 Literature Survey 4

2.3 Concluding Remarks 7

3 MODELLING OF DUAL PERMANENT MAGNET SYNCHRONOUS MOTOR **8**

3.1 Overview 8

3.2 PMSM Structure 8

3.3 Dual PMSM 10

3.4 Mathematical Model of dual PMSM 11

3.5 Motor Specifications 15

3.6	Model Validation	15
3.6.1	Results and Discussion	16
3.7	Concluding Remarks	16
4	METHODOLOGY	17
4.1	Overview	17
4.2	Block Diagram	17
4.3	Concluding Remarks	19
5	CONTROLLER DESIGN	20
5.1	Overview	20
5.2	Proportional-Integral Controller	20
5.3	Fuzzy Logic Controller	21
5.4	Sliding Mode Controller	24
5.4.1	SMC Design	25
5.5	Novel Fuzzy-Sliding Mode Controller	28
5.6	Concluding Remarks	30
6	RESULTS AND DISCUSSION	31
6.1	Overview	31
6.2	Load Torque Characteristics	31
6.3	PI Controller	32
6.3.1	Speed Response-Without Parameter Variation	32
6.3.2	Speed Response-With Parameter Variation	33
6.3.3	Results and Discussion	34
6.4	Fuzzy Logic Controller	35
6.4.1	Speed Response-Without Parameter Variation	35
6.4.2	Speed Response-With Parameter Variation	36
6.4.3	Results and Discussion	38
6.5	Sliding Mode Controller	38
6.5.1	Speed Response-Without Parameter Variation	38
6.5.2	Speed Response-With Parameter Variation	40
6.5.3	Results and Discussion	41

6.6	Novel Fuzzy-Sliding Mode Controller	42
6.6.1	Speed Response-Without Parameter Variation	42
6.6.2	Speed Response-With Parameter Variation	43
6.6.3	Results and Discussion	44
6.7	Overall Comparison of Controllers With and Without Parameter Variation . . .	45
6.8	Concluding Remarks	45
7	CONCLUSION	46
	References	47
	List of Publications	50

List of Tables

3.1	Specification of PMSM[29]	15
5.1	Gain values for PI controller	21
5.2	Rule for speed control.	23
5.3	Rule for active damping control.	23
5.4	Gain values for SMC controller	28
5.5	Fuzzy rule for tuning parameter	29
6.1	Settling time of dual PMSM by using PI controller with and without parameter variation	35
6.2	Settling time of dual PMSM using fuzzy logic controller with and without parameter variation	38
6.3	Settling time of dual PMSM by using Sliding mode controller with and without parameter variation	41
6.4	Settling time of dual PMSM by using Fuzzy-Sliding mode controller with and without parameter variation	44
6.5	Settling time of dual PMSM by using different controllers without parameter variation	45
6.6	Settling time of dual PMSM by using different controllers with parameter variation	45

List of Figures

3.1	Induction Motor vs PMSM[25]	9
3.2	Types of PMSM motor[26]	9
3.3	Basic block diagram of PMSM motor	10
3.4	Single inverter dual PMSM drive system	11
3.5	Equivalent circuit of PMSM.	11
3.6	Single inverter dual PMSM drive system	12
3.7	Open loop Torque characteristics of dual PMSM	15
3.8	Open loop Speed characteristics of dual PMSM	16
4.1	Block diagram of control scheme for dual PMSM	17
5.1	Basic block diagram of PI controller[27]	20
5.2	Basic block diagram of Fuzzy logic controller[28]	22
5.3	(a) Reaching Phase (b) Sliding Phase[24]	25
5.4	Basic structure of Fuzzy Sliding Mode Controller	29
6.1	Load torque variation	31
6.2	Dual PMSM speed response using PI controller without active damping	32
6.3	Dual PMSM speed response using PI controller with active damping	33
6.4	Dual PMSM speed response using PI controller without active damping (when the parameter is varied)	33
6.5	Dual PMSM speed response using PI controller with active damping (when the parameter is varied)	34
6.6	Dual PMSM speed response using fuzzy logic controller without active damping	35
6.7	Dual PMSM speed response using fuzzy logic controller with active damping	36

6.8	Dual PMSM speed response using Fuzzy logic Controller without active damping (when the parameter is varied)	37
6.9	Dual PMSM speed response using Fuzzy logic Controller with active damping (when the parameter is varied)	37
6.10	Dual PMSM speed response using sliding mode controller without active damping	39
6.11	Dual PMSM speed response using sliding mode controller with active damping	39
6.12	Dual PMSM speed response using Sliding mode Controller without active damping (when the parameter is varied)	40
6.13	Dual PMSM speed response using Sliding mode Controller with active damping (when the parameter is varied)	41
6.14	Dual PMSM speed response using Fuzzy-Sliding mode Controller without active damping	42
6.15	Dual PMSM speed response using Fuzzy-Sliding mode Controller with active damping	43
6.16	Dual PMSM speed response using Fuzzy-Sliding mode Controller without active damping (when the parameter is varied)	43
6.17	Dual PMSM speed response using Fuzzy-Sliding mode Controller with active damping (when the parameter is varied)	44

Abbreviations

dq	Direct quadrature axis
FLC	Fuzzy Logic Control
FOC	Field Oriented Control
FSMC	Fuzzy Sliding Mode Control
MPC	Model Predictive Control
MRAS	Model Reference Adaptive System
PI	Proportional Integral
PLL	Phase Locked Loop
PMSM	Permanent Magnet Synchronous Motor
SIDIM	Single Inverter Dual Induction Motor
SMC	Sliding Mode Control
ST – DTC	Standard Direct Torque Control
SVM – DTC	Space Vector Modulation Direct Torque Control
VSI	Voltage Source Inverter

Notations

L_d	d axis inductance
L_q	q axis inductance
v_d	Voltage applied on direct axis
v_q	Voltage applied on quadrature axis
i_d	Stator current on direct axis
i_q	Stator current on quadrature axis
w_e	Electrical angular velocity
w_r	Mechanical Speed
T_e	Electromagnetic torque
T_L	Load torque
λ_m	Magnetic flux linkage
R_s	Stator winding resistance
T_D	Dry friction
B	Viscous friction
J	Moment of inertia
p	Number of poles
N_s	Synchronous speed

Chapter 1

INTRODUCTION

1.1 General Background

Permanent magnet synchronous motors (PMSM) are widely utilized in various industrial applications such as machine tools, industrial robots, etc. due to their high torque to weight ratio, high power density, high efficiency, reliability, and ease of maintenance[1]. It is industrially relevant and a better alternative for induction motors. In a dual induction motor (IM), the parallel operation is stable due to the presence of slip. But in dual PMSM due to the variation in load torque there is an oscillation that occurs in one motor and it loses synchronism. So, speed control techniques are essential for dual PMSM for its stable operation.

In a PMSM, a permanent magnet replaces the dc field winding of rotor to create the air gap magnetic flux. The presence of this permanent magnet reduces electrical losses in the machine field winding and it enhances the thermal properties, overall efficiency of the system. This motor is also lighter and has a high power-to-weight ratio due to the absence of mechanical components like brushes and slip rings which increases efficiency and reliability.

In high-power applications such as aircraft, traction applications, and conveyer belts, by using one PMSM alone , it cannot be provide enough torque for its proper operation. So multi-motor drive systems are used in these applications to provide enough torque and to reduce cost[2]. To drive these multi-motor drive systems multiphase inverters are essential. As compared with four-phase and five-phase inverters a single three-phase inverter with multi-motor drives has lower economic feasibility because of its smaller number of switching devices. Con-

ventionally single inverter dual induction motor (SIDIM) are used in industrial applications and their parallel operation is stable.

Recently, in industries, permanent magnet synchronous motors replace induction motors due to their transcendent properties. In these motors, the parallel operation is based upon the master/ slave control scheme. The motor whose speed to be controlled is selected as the master and the other is selected as the slave which is works in an open loop. In dual PMSM the speed of two motors is equal when the load torque of both motors is the same. But in different load torque, the rotor position of two motors will be different even at the same speed. Also there is an oscillations are occurred in the slave motor and it leads to instability. So, speed control techniques play an important role in the parallel operation of dual PMSM to improve the system performance.

1.2 Problem Definition

Conventionally, various control techniques are employed in dual PMSM for its speed control and stable operation. But it has some limitations too. By analysing open loop performance of the system it is found that small variations in system parameters lead to large variations in system performance. So robust control techniques are essential for dual PMSM to achieve a good response against the parameter variations of two motors. Therefore, various speed control techniques are adopted for dual PMSM to improve the system performance.

In a dual PMSM, the speed of the two motors and its load torque must be same to achieve the stable operation. But in different load torque, there is an oscillations occurred in the slave motor and it affects the stable operation of dual PMSM. So, here an active damping control is used to suppress the oscillations and it provide a stable operation.

1.3 Objectives

- To develop mathematical model for dual PMSM
- To compare the performance of dual PMSM using different control techniques (PI, FUZZY, SMC) with and without active damping control (without parameter variation).

- To compare the performance of dual PMSM using different control techniques (PI, FUZZY, SMC) with and without active damping control (when the parameter is varied).
- To design a novel Fuzzy SMC controller with active damping control for a single inverter dual PMSM drive system.

1.4 Organisation of the Report

This project organized in 7 chapters. Chapter 1 titled by introduction includes general background, problem definition, objective and thesis outline. Chapter 2 includes the literature review done on the work. In chapter 3 gives the basic idea and mathematical derivation of dual permanent magnet synchronous motor. Chapter 4 discuss about the overall control scheme. Chapter 5 deals with design and implementation of various speed control techniques with active damping control for dual PMSM. Chapter 6 describes the simulation and analysis of result and the overall conclusion drawn from this project work is discussed in chapter 7.

Chapter 2

LITERATURE REVIEW

2.1 Overview

This chapter includes the previous work related to thesis.

2.2 Literature Survey

In recent years, there are various control strategies accessible for dual PMSM drive systems. Those control strategies include nonlinear control methods and hardware implementations [3].

The rotor position estimation plays an important role in controlling dual PMSM because of the rotor flux from the permanent magnet that is attached to the rotor. So, the speed or position sensor is attached to the shaft of the motor. But these sensors have some disadvantages such as increased complexity, extra cost, weight, and reduced reliability. To overcome these disadvantages, scholars show great interest in the sensorless speed control technique [4].

In [5] adopted a sensorless speed control technique in a dual induction motor drive system. Here the usage of speed and position sensors is avoided by proposing an adaptive observer scheme for the detection of rotor position.

In paper [6] provides a sensorless control based on a model reference adaptive system and it is used for speed estimation. Here the speed is estimated by using a model reference adaptive system and the initial rotor position is estimated by dc excitation. The complexity of mathematical modeling is reduced based on three orthogonal subspaces. In the MRAS method, two models have been chosen. One is a mathematical model which is taken as an adaptive

motor and the motor is taken as a reference. The adaptive mechanism converges to zero error between two models by taking the corrective information of rotor speed. Finally, the stability of dual PMSM drive is verified by using Popov criteria and the proposed sensorless scheme which gives the good dynamic response and steady-state accuracy, good speed regulation capability, and transient response.

In [7] also includes the MRAS scheme for obtaining the speed of motors. Similar to the early proposed scheme, the FOC is used as a speed controller. But the difference is; that in the MRAS scheme the motor is a reference model and the current of the motor is set as an adjustable model. The rotor speed is obtained by comparing these two models in the adaption mechanism and it ensures the stability of the system. The proposed strategy in this paper gives good speed performance under different load conditions and it can be used as a drive system for single inverter dual PMSM.

In [8], the paper represents a flux sliding mode observer with a soft phase-locked loop method for the rotor and speed estimation. To reduce the complexity of controller structure, an equivalent flux linkage concept is used to replace the conventional sign function with the sigmoid function as it reduces the chattering. In addition to this, for better control, a minimum of four current regulators are involved in this proposed strategy. At very low speed, the occurrence of noise and harmonic affects the accuracy of rotor position. To avoid that problem, a phase-locked loop (PLL) is used. The great advantage of this strategy is that it provides smooth rotor position and estimation of speed.

Previous researchers have been only focusing on the averaging techniques [6],[7]. The fuzzy logic controller is an emerging control technique used in industrial applications which have complexities in solving a mathematical model or restrictions in performance with a conventional linear scheme. In [9] proposed a scheme of a fuzzy logic speed controller with a reduced rule base for dual PMSM drives. It consists of a standard fuzzy speed controller and a simplified fuzzy speed controller. The standard fuzzy speed controller contains 49 rules and the proposed or simplified fuzzy speed controller consist of 9 rules. In this study, the membership function and fuzzy sets for input or output variables are selected by trial and error to achieve optimum drive performance. The proposed fuzzy logic design gives better performance than the standard design under different types of load disturbances.

In [10] includes optimization of torque in two motors by using perturbation and observation method which is based on a fuzzy logic controller. Compared with other methods, the fuzzy

logic controller is simple and it gives a better fast response. In this study, the Mamdani method is used to obtain the fuzzy interface. Compared to the conventional perturbation and observation method, the proposed scheme improves the time response and steady-state oscillation.

Zhang Jian et.al [11] present an optimized control technique for the electric vehicle propulsion system. It consists of a single digital signal processor to set the working mode of the inverter in an acceptable value by using measurement or estimation of real-time load status and it coordinates the work between two motors. Then it will improve the overall efficiency of the system.

In [12] includes a unified model of the virtual average machine and in this study, they consider two auxiliary conditions. The first one is used to minimize the current supplied by the inverter and the second one is used for maximizing the efficiency of the motor. In [13], a standard controller for a single PMSM can be readily modified to support parallel PMSM by adding a few blocks without changing the controller. It gives a detailed explanation of the stability and determinacy of the system.

Model predictive control is an advanced process control technique. In [14], model predictive control is used to control the speed and vibration of dual inertia PMSM drives. The proposed control strategy combines the safety and physical limitations of drive to control the problems associated with future constraint violations. Here the main goal of a speed control system is to ensure load speed which tracks the command speed. MPC controller is highly efficient in dealing with inherent torque and motor constraints.

The paper [15] presents a predictive torque control approach for dual parallel PMSM. It is used to minimize the cost function and it results in minimum current. Since there is no current controller then it leads to torque ripples. To reduce this ripple here a split and seek algorithm is implemented. So, it determines the state of the system and ensures stability and acceptable performance in terms of efficiency and torque ripple. But it also increases the complexity of the system.

In [16], includes a two-step model predictive control for currents in two-level VSI fed in dual PMSM. This study consists of two steps. One is to find a phase that has a maximum current error and the second step is to change the switching signals into two phases. As a result, switching frequency is reduced and it leads to less computational burden. The merit of this control strategy is good operations under dynamic performance and steady-state operation.

Hybrid control is a combination of two or more controllers. In [17], a fuzzy sliding mode observer with dual SOGI-FLL is used in dual PMSM. In this paper, a sensorless control scheme based on a sliding mode observer and dual second-order generalized integrator frequency locked loop is used to improve the performance of PMSM. To adjust the observer gain and to reduce the chattering the FLC is correlated to SMO. To filter the residual higher-order harmonics and suppress the external noise the SOGI-FLL is used.

Xueqing et.al [18] propose a hybrid direct torque control scheme for dual three-phase PMSM. It is a combination of standard (ST) DTC and space vector modulation (SVM) based DTC. In ST-DTC the dynamic response is faster and it leads to torque and flux ripples. But in SVM-DTC it reduces the torque and flux ripple and it slows down the dynamic response. So, the combination of these two techniques improves the overall performance.

Tounsi kamal et.al [19] present an extended Kalman filter (EKF) based sliding mode speed control for dual PMSM. The sliding mode control is used for controlling the speed and current and EKF is used for the sensorless control scheme. In SMC, there are two stages. The first stage is to choose a sliding surface and the second stage is used for designing a control law. Here the important task of the EKF is to determine a good estimate of state variable and unknown load torque. The sliding mode has several merits such as robustness, high accuracy, stability, and low settling time.

2.3 Concluding Remarks

This chapter discusses earlier work related to the thesis and draws the conclusion that these previous strategies are better for dual PMSM without parameter variation. However, the stability and performance of dual PMSM during motor parameter fluctuation are not considered in these literatures

Chapter 3

MODELLING OF DUAL PERMANENT MAGNET SYNCHRONOUS MOTOR

3.1 Overview

This chapter discusses about the structure, operation and mathematical modelling of a permanent magnet synchronous motor.

3.2 PMSM Structure

Permanent Magnet Synchronous Motor (PMSM) is a type of AC synchronous motor and it is a cross between an induction motor and a brushless dc motor. It is extensively used in industrial applications because of its high-performance characteristics[20].

This rotating electric motor contains a stator and rotor. Here, a Permanent magnet is used as a rotor and a conventional three-phase winding as a stator. Normally a synchronous motor needs an AC supply for stator winding and a DC supply for rotor winding. But in PMSM, conventional field winding of the rotor is replaced by permanent magnets. So, it only uses an AC supply for stator winding. The rotor turns at the speed of the stator spinning field and that speed is called synchronous speed.

Synchronous speed of a motor,

$$N_s = \frac{120f}{p} \quad (3.1)$$

Where, f = frequency of AC supply and p is number of poles

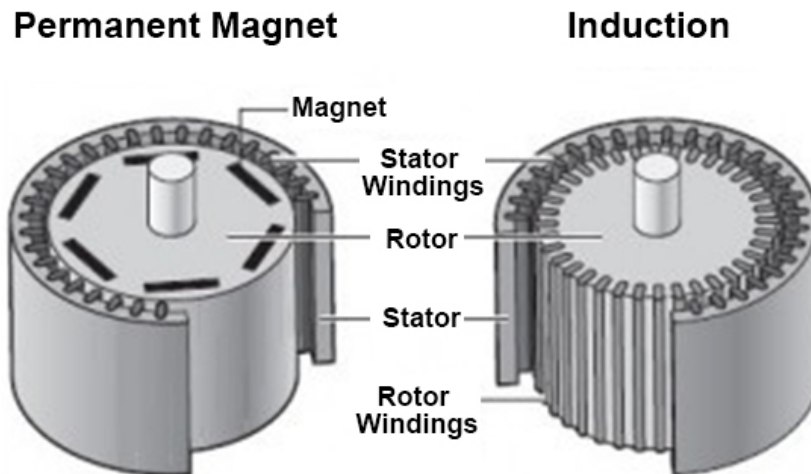


Figure 3.1: Induction Motor vs PMSM[25]

The operation of PMSM relies on the pivoting magnetic field of the stator and the steady magnetic field of the rotor. Iron, boron, etc. are used for making permanent magnets in the PMSM due to their high permeability. These permanent magnets are mounted on the rotor. Based upon the mounting of a permanent magnet, PMSM is classified into 2.

- (i) Surface-mounted PMSM (ii) Interior PMSM

In surface-mounted PMSM, the permanent magnet is placed on the surface of the rotor. This arrangement gives a uniform air gap, no reluctance torque, and large dynamic performance. It is widely used in high-speed applications. In interior PMSM, the permanent magnets are implanted inside the rotor and it contains reluctance torque.

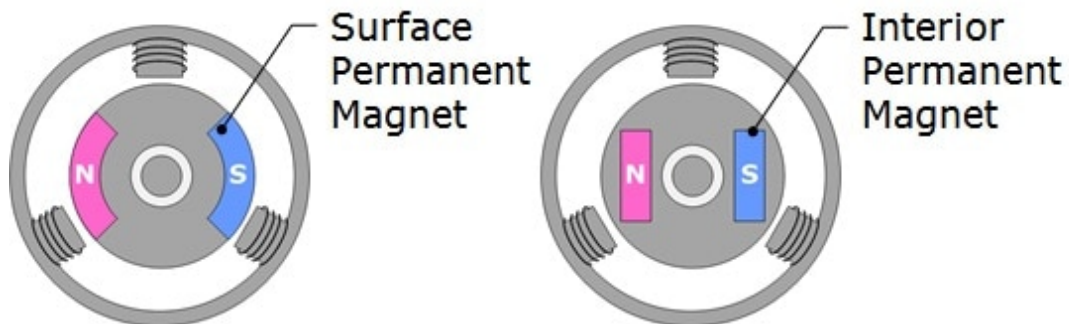


Figure 3.2: Types of PMSM motor[26]

Fig 3.3 indicates the basic block diagram of PMSM motor drives. It contains an inverter, PMSM, controller, and position sensor. The inverter converts the constant dc voltage to variable

ac voltage and it is commonly used in adjustable speed drives. When a PMSM motor working in the absence of damper winding, then it needs a rotor position sensor in the rotor shaft and to detect the rotor position.

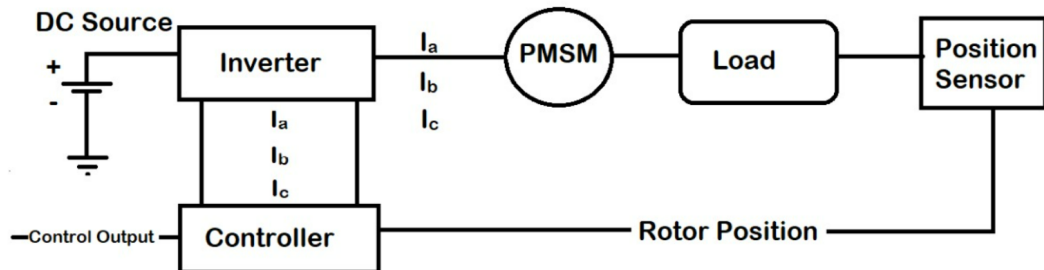


Figure 3.3: Basic block diagram of PMSM motor

PMSM is widely used in low to high-power applications. Such as machine tools, traction applications, conveyor belts, robotics, etc[21].

3.3 Dual PMSM

Applications like conveyor belts, electric train tractions, aircraft, wind power generations, etc. need high power requirements [1]. To achieve this requirement, high power is essential and it will increase the size of the machine. So, the multi-motor drive system arises to overcome this disadvantage.

Multi motor drive system increases their mechanical simplicity, flexibility, and safety operations. But the need for the inverter makes the dual inverter dual-motor drive configuration economically less competitive [22]. Therefore, in recent years, single inverter dual PMSM drives are rising to reduce the size and cost of the single motor drives and it offers lower economic feasibilities [23].

Fig 3.4 represents the schematic diagram of a dual PMSM drive system; which consists of an inverter that inverts dc to ac supply meanwhile the motors are fed with a single inverter.

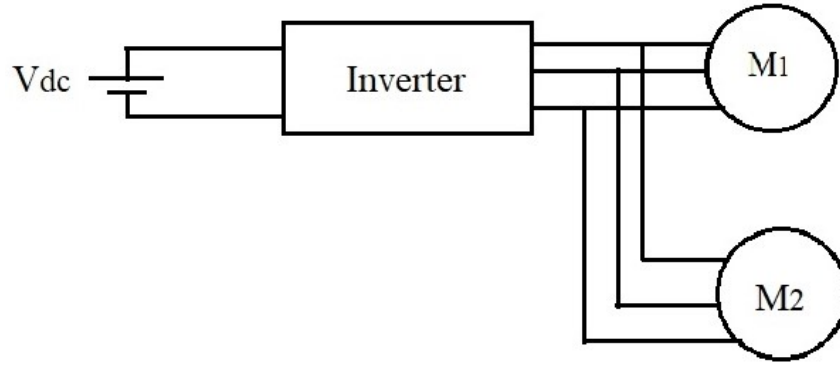


Figure 3.4: Single inverter dual PMSM drive system

3.4 Mathematical Model of dual PMSM

Vectors are the representation of balanced 3-phase currents and voltages in terms of magnitude and direction. The sum of three vectors is zero for balanced three-phase systems.

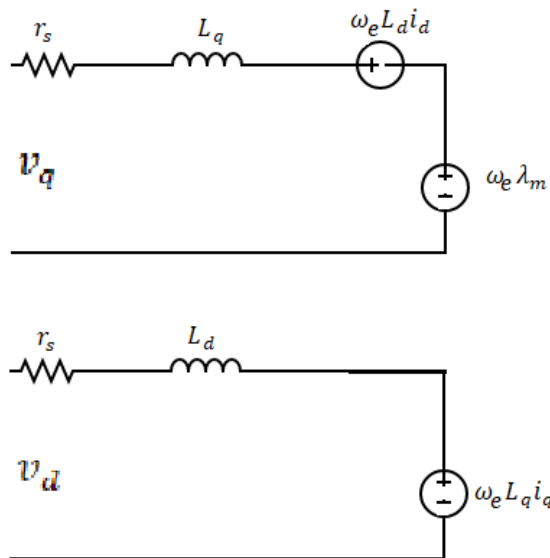


Figure 3.5: Equivalent circuit of PMSM.

The exact equivalent circuit of PMSM in dq reference frame is as shown in Fig. 3.5 is obtained by applying the Park transformation. Park transformation is a most commonly used transformation for transform abc reference frame to the dq reference frame for motor control.

Fig 3.6 illustrates the projections on the dq axes and the three-phase vectors at a particular instant. abc to dq transformation which means transforming a three-phase (abc) signal to a $dq0$ rotating reference frame.

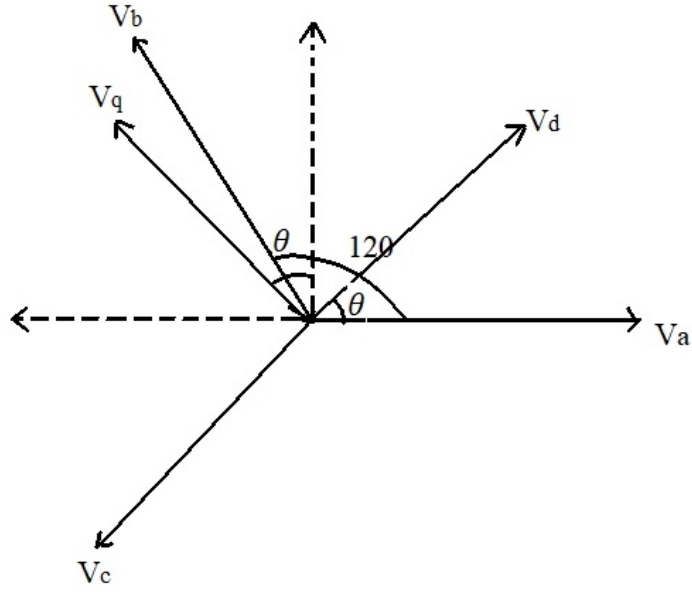


Figure 3.6: Single inverter dual PMSM drive system

The vectors in abc reference frame can easily transform to the $dq0$ reference frame with some trigonometric calculations. Using trigonometric computation from Fig 3.6. From the d axis, we get,

$$V_a = V_d \cos \theta \quad (3.2)$$

$$V_b = V_d \cos(\theta - 120) \quad (3.3)$$

$$V_c = V_d \cos(\theta + 120) \quad (3.4)$$

From the q axis,

$$V_a = -V_q \sin \theta \quad (3.5)$$

$$V_b = -V_q \sin(\theta - 120) \quad (3.6)$$

$$V_c = -V_q \sin(\theta + 120) \quad (3.7)$$

Matrix representation is,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 1 \\ \cos(\theta - 120) & -\sin(\theta - 120) & 1 \\ \cos(\theta + 120) & -\sin(\theta + 120) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \quad (3.8)$$

abc to dq transformation is,

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - 120) & \cos(\theta + 120) \\ -\sin \theta & -\sin(\theta - 120) & -\sin(\theta + 120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3.9)$$

Here V_d and V_q are projections of the vector along with the ‘quadrature’ and ‘direct’ axis respectively. The measured rotor position is taken as θ for the conversion. The rotor reference frame is the new reference frame obtained from the conversion of stator quantities. The permanent magnet flux is zero along the q -axis since the q -axis is aligned with the mechanical placement of the magnets. The dq motor model in the rotor reference frame helps for a simple controller design as it converts back-emf voltages, applied voltages, and stator currents into DC quantities. Also, the torque produced is in terms of currents along with the d and q axis.

Applying Kirchhoff’s current and voltage laws in the d and q -axis circuit shown in fig 3.5 results in

$$V_{d1,2} = R_s i_{d1,2} + L_d \frac{di_{d1,2}}{dt} - \omega_{e1,2} L_q i_{q1,2} \quad (3.10)$$

$$V_{q1,2} = R_s i_{q1,2} + L_q \frac{di_{q1,2}}{dt} + \omega_{e1,2} L_d i_{d1,2} + \omega_{e1,2} \lambda_m \quad (3.11)$$

Flux in the d and q axis is

$$\lambda_{d1,2} = L_d i_{d1,2} + \lambda_m \quad (3.12)$$

$$\lambda_{q1,2} = L_q i_{q1,2} \quad (3.13)$$

Substitute equation (3.12) in (3.10) and (3.13) in (3.11)

$$V_{d1,2} = R_s i_{d1,2} + L_d \frac{di_{d1,2}}{dt} - \omega_{e1,2} \lambda_{q1,2} \quad (3.14)$$

$$V_{q1,2} = R_s i_{q1,2} + \frac{d\lambda_{q1,2}}{dt} + \omega_{e1,2} \lambda_{d1,2} \quad (3.15)$$

Stator voltage in the d and q axis is

$$V_{d1,2} = R_s i_{d1,2} + \frac{d\lambda_{d1,2}}{dt} - \omega_{e1,2} \lambda_{q1,2} \quad (3.16)$$

$$V_{q1,2} = R_s i_{q1,2} + \frac{d\lambda_{q1,2}}{dt} + \omega_{e1,2} \lambda_{d1,2} \quad (3.17)$$

Electromagnetic torque equation

$$T_{e1,2} = \frac{3}{2} * \frac{p}{2} * (\lambda_{d1,2} i_{q1,2} - \lambda_{q1,2} i_{d1,2}) \quad (3.18)$$

Mechanical torque equation

$$T_{e1,2} = T_L + T_D + B\omega_{r1,2} + J \frac{d\omega_{r1,2}}{dt} \quad (3.19)$$

Mechanical speed equation

$$\omega_{r1,2} = \int \left(\frac{T_{e1,2} - T_L - T_D - B\omega_{r1,2}}{J} \right) dt \quad (3.20)$$

Electrical speed

$$\omega_{e1,2} = \frac{p}{2} \omega_{r1,2} \quad (3.21)$$

Here,

$L_d = d$ axis inductance

$L_q = q$ axis inductance

$v_d =$ Voltage applied on direct axis

$v_q =$ Voltage applied on quadrature axis

$i_d =$ Stator current on direct axis

$i_q =$ Stator current on quadrature axis

$\omega_e =$ Electrical angular velocity

$\omega_r =$ Mechanical speed

$T_e =$ Electromagnetic torque

$T_L =$ Load torque $\lambda_m =$ Magnetic flux linkage

$R_s =$ Stator winding resistance

$T_D =$ Dry friction

$B =$ Viscous friction

$J =$ Moment of inertia

$p =$ Number of poles

3.5 Motor Specifications

Table 3.1 indicates the specification of PMSM used in this work.

Table 3.1: Specification of PMSM[29]

Sl.No	Parameter	Specification
1	Rated speed	2000rpm
2	Rated torque	5 Nm
3	Stator resistance	3.18 Ω
4	d axis inductance, L_d	7.5mH
5	q axis inductance, L_q	7.5mH
6	Magnetic flux linkage, λ_m	0.325 Wb
7	No. of poles	4
8	Moment of inertia, J	0.00046 Kgm^2

3.6 Model Validation

After design the mathematical model of the Permanent Magnet Synchronous Motor it is validated in MATLAB/simulink. Fig 3.7 and 3.8 shows the opeloop characteristics of torque and speed respectively.

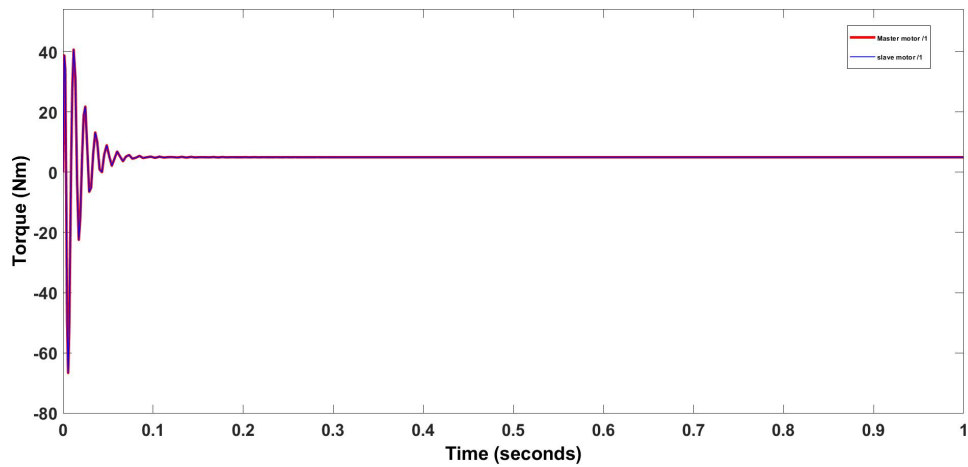


Figure 3.7: Open loop Torque characteristics of dual PMSM

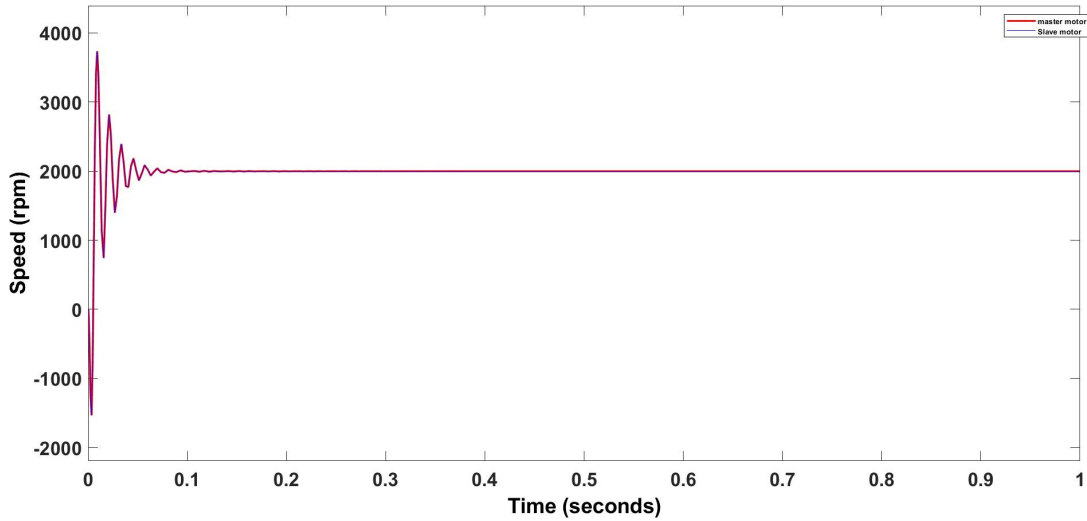


Figure 3.8: Open loop Speed characteristics of dual PMSM

3.6.1 Results and Discussion

By analyzing the model, following conclusions are obtained even though the system provide rated speed at rated torque.

- System takes relatively large time to achieve the reference speed.
- Small variation in system parameter leads to a large variation in system performance.

3.7 Concluding Remarks

The mathematical model of permanent magnet synchronous motor and its MATLAB simulation is discussed in this chapter. In the open loop characteristics, system achieve rated speed at a rated torque. By the analysis of system model, it is inferred that a small variation in system parameter leads to a substantial variation in system performance and also, during variable speed application it is necessary to achieve a desired speed other than rated speed. So a speed controller is essential for dual PMSM to track the reference speed and to improve the system performance.

Chapter 4

METHODOLOGY

4.1 Overview

This chapter explains the block diagram of control scheme for a dual PMSM.

4.2 Block Diagram

Figure 4.1 represents the block diagram of overall control scheme.

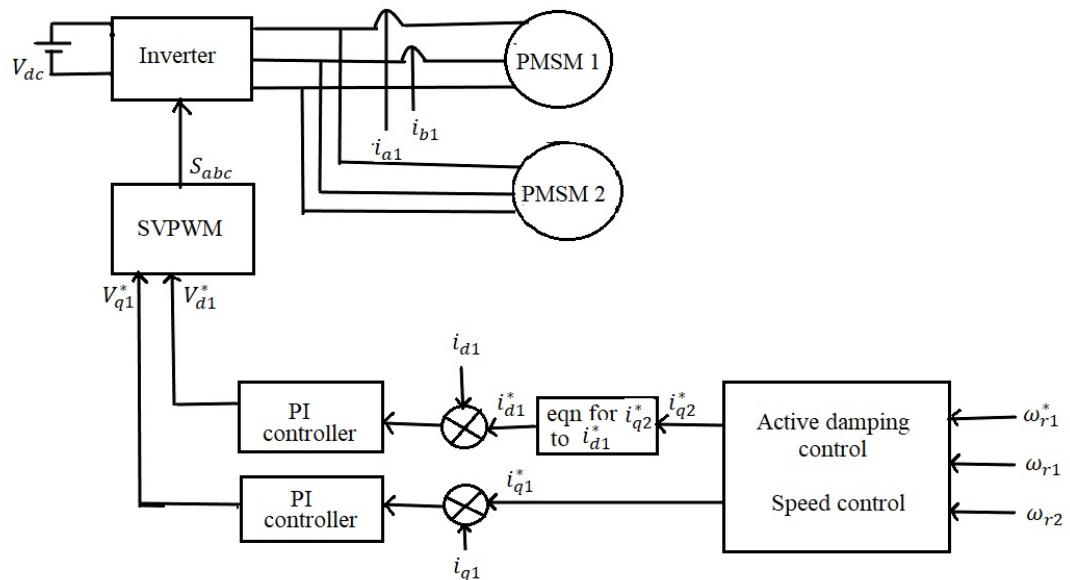


Figure 4.1: Block diagram of control scheme for dual PMSM

Two permanent magnet synchronous motors have the same specifications and are connected in parallel. One motor is a master whose speed is to be controlled and the other is a slave which works by the controlled input voltage of the master. In this control scheme, mainly two control actions are taking place. The first one is speed control and the second is active damping control. Speed control is used to achieve the reference speed and active damping control is used to suppress the oscillations in the slave motor due to different load torque. Reference speed and actual speed of both motors are given to the input of the controller. Then the output of speed and active damping controller is the reference q-axis current of master and reference q-axis current of slave respectively. The reference q-axis current of the master motor is compared with the actual q-axis current of the motor and the q-axis current slave motor is converted to d axis current of the master by using an equation which is derived from,

$$\begin{aligned} V_{d1,2} &= R_s i_{d1,2} + L_s \frac{di_{d1,2}}{dt} - \omega_{r1,2} L_s i_{q1,2}. \\ V_{q1,2} &= R_s i_{q1,2} + L_s \frac{di_{q1,2}}{dt} + \omega_{r1,2} L_s i_{d1,2} + \omega_{r1,2} \phi_f. \end{aligned} \quad (4.1)$$

d and q axis voltage of two motors are,

$$\begin{bmatrix} V_{d1,2} \\ V_{q1,2} \end{bmatrix} = \begin{bmatrix} R_s & -\omega_{r1,2} L_s \\ \omega_{r1,2} L_s & R_s \end{bmatrix} \begin{bmatrix} i_{d1,2} \\ i_{q1,2} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_{r1,2} \phi_f \end{bmatrix} \quad (4.2)$$

$$\begin{bmatrix} i_{d2}^* \\ i_{q2}^* \end{bmatrix} = \begin{bmatrix} R_s & -\omega_r L_s \\ \omega_r L_s & R_s \end{bmatrix}^{-1} \left(\begin{bmatrix} V_{d2} \\ V_{q2} \end{bmatrix} - \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix} \right) \quad (4.3)$$

Due to the difference in rotor position, the voltage relationship between two motors are

$$\begin{bmatrix} V_{d2} \\ V_{q2} \end{bmatrix} = \begin{bmatrix} \cos \Delta\theta & \sin \Delta\theta \\ -\sin \Delta\theta & \cos \Delta\theta \end{bmatrix} \begin{bmatrix} V_{d1} \\ V_{q1} \end{bmatrix} \quad (4.4)$$

Substitute equation 4.2 and 4.4 in 4.3

$$\begin{aligned} \begin{bmatrix} i_{d2}^* \\ i_{q2}^* \end{bmatrix} &= \begin{bmatrix} R_s & -\omega_r L_s \\ \omega_r L_s & R_s \end{bmatrix}^{-1} \left\{ \begin{bmatrix} \cos \Delta\theta & \sin \Delta\theta \\ -\sin \Delta\theta & \cos \Delta\theta \end{bmatrix} \left\{ \begin{bmatrix} R_s & -\omega_r L_s \\ \omega_r L_s & R_s \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} \right. \right. \\ &\quad \left. \left. + \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix} \right\} - \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix} \right\} \end{aligned} \quad (4.5)$$

$$\begin{bmatrix} i_{d2}^* \\ i_{q2}^* \end{bmatrix} = \begin{bmatrix} \cos \Delta\theta & \sin \Delta\theta \\ -\sin \Delta\theta & \cos \Delta\theta \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} + \begin{bmatrix} R_s & -\omega_r L_s \\ \omega_r L_s & R_s \end{bmatrix}^{-1} \begin{bmatrix} \cos \Delta\theta & \sin \Delta\theta \\ -\sin \Delta\theta & \cos \Delta\theta \end{bmatrix} \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix} - \begin{bmatrix} 0 \\ \omega_r \phi_f \end{bmatrix} \begin{bmatrix} R_s & -\omega_r L_s \\ \omega_r L_s & R_s \end{bmatrix}^{-1} \quad (4.6)$$

$$\begin{bmatrix} i_{d2}^* \\ i_{q2}^* \end{bmatrix} = \begin{bmatrix} \cos \Delta\theta & \sin \Delta\theta \\ -\sin \Delta\theta & \cos \Delta\theta \end{bmatrix} \begin{bmatrix} i_{d1} \\ i_{q1} \end{bmatrix} + \frac{\omega_r \phi_f}{R_s^2 + \omega_r^2 L_s^2} \begin{bmatrix} R_s & \omega_r L_s \\ -\omega_r L_s & R_s \end{bmatrix} \begin{bmatrix} \sin \Delta\theta \\ \cos \Delta\theta - 1 \end{bmatrix} \quad (4.7)$$

The effect of the stator resistance can be disregarded if the motor speed is sufficiently high, it indicates that

$$\omega_r \gg R_s \quad (4.8)$$

Then,

$$\frac{\omega_r \phi_f}{R_s^2 + \omega_r^2 L_s^2} \approx \frac{\phi_f}{\omega_r L_s^2} \quad (4.9)$$

$$\begin{bmatrix} i_{d2}^* \\ i_{q2}^* \end{bmatrix} = \begin{bmatrix} \cos \Delta\theta i_{d1} + \sin \Delta\theta i_{q1} \\ -\sin \Delta\theta i_{d1} + \cos \Delta\theta i_{q1} \end{bmatrix} + \begin{bmatrix} \frac{\phi_f}{L_s} \cos \Delta\theta - 1 \\ \frac{-\phi_f}{L_s} \sin \Delta\theta \end{bmatrix} \quad (4.10)$$

Equation used for converting i_{q2}^* to i_{d1}^* is represented as

$$i_{d1}^* = \frac{-i_{q2}^* + i_{q1} \cos \Delta\theta - \frac{\phi_f}{L_s} \sin \Delta\theta}{\sin \Delta\theta} \quad (4.11)$$

This reference d and q axis current of master motor is compared with the actual d and q axis current. By using a current controller, this reference current is converted to reference voltages ie, V_d and V_q . These reference voltages, generate a gate pulse to trigger the inverter switches by means of Space Vector Pulse Width Modulation(SVPWM) technique. Using a three phase inverter the control signals in abc reference frame is applied to the terminals of dual PMSM.

4.3 Concluding Remarks

This chapter provides a detailed explanation of control scheme for dual PMSM.

Chapter 5

CONTROLLER DESIGN

5.1 Overview

From the analysis of the system model, it is inferred that a small variation in motor parameters leads to a large variation in system performance. So various speed control techniques with active damping control are designed to improve the system performance using different controllers (PI, FUZZY, SMC, FUZZY-SMC) against with and without parameter variation. This chapter provides the design of these control strategies.

5.2 Proportional-Integral Controller

A controller is a tool used to keep a process variables value at the predetermined level. Proportional integral controller is referred to as PI. The output is equal to the sum of the proportional and integral of the error signal, and it eliminate the steady state error caused by a P controller.

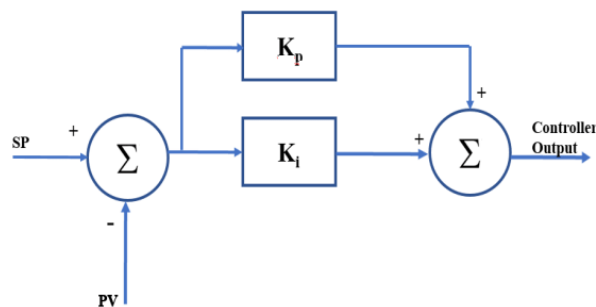


Figure 5.1: Basic block diagram of PI controller[27]

PI controller is represented as

$$u(t) = K_p e(t) + K_i \int e(t) dt \quad (5.1)$$

A PI controller is a feedback controller that determines an error signal by comparing the output of the system -in this case , the actual speed of master motor and the reference speed. This error signal is then multiplied by the proportional and integral constants in the PI control loop. The output of the PI controller is a reference current for the current control loop.

Table 5.1 indicates the gain values used for PI controller with and without parameter variation.

Table 5.1: Gain values for PI controller

	Without parameter variation	With parameter variation
Without active damping control	$K_p = 0.0084$ $K_i = 0.9445$	$K_p = 3.93345$ $K_i = 223.11213$
With active damping control	$K_p = 2449.6$ $K_i = 0.05403$	$K_p = 0.845$ $K_i = 0.9445$

The drawbacks of the PI controller include its high initial overshoot and slow reaction to unexpected disturbances.

5.3 Fuzzy Logic Controller

Fuzzy logic controllers (FLC) are among the best solutions for plants that struggle to derive mathematical models. Fuzzy logic which is based on human reasoning, can turn a set of linguistic rules based on professional expertise into an automatic control approach. No mathematical models are required to solve an issue, but talent is required to write the rules for a certain FL controller. The idea behind FLC is to use the qualitative information of a system to develop an

effective controller, and this idea is further backed by the claim that a fuzzy control algorithm embeds the intuition and expertise of an operator designer and researcher.

Compared to traditional control methods, FLC has proven to be most effective in complicated, poorly defined issues that can be managed by a skilled human operator without being aware of their underlying dynamics.

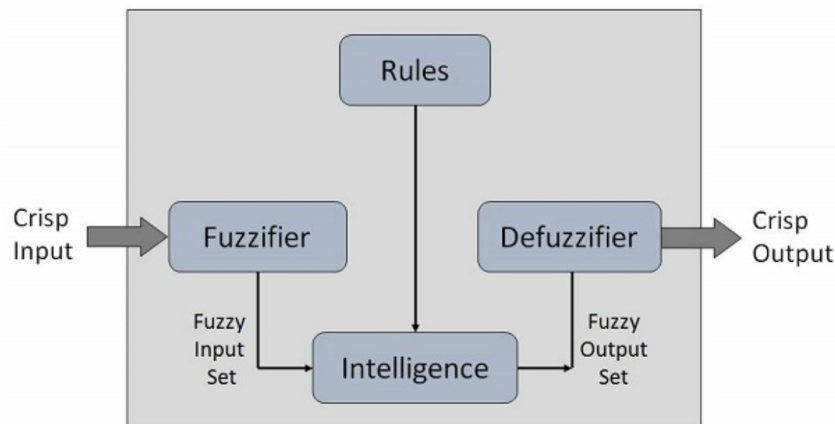


Figure 5.2: Basic block diagram of Fuzzy logic controller[28]

Fig 5.2 represents the basic block diagram of fuzzy logic controller. An FLC system consists of a fuzzifier, a fuzzy knowledge base, an inference engine, and a defuzzifier as its main parts. Quantities that are crisp are changed to fuzzy by the fuzzifier. Information regarding all fuzzy input-output relationships is kept in the fuzzy knowledge base. The input variables to the fuzzy rule base and the output variables to the controlled plant are defined by the membership functions included in it.

- **Step 1**- Determine state variable, input and output for the system.
- **Step 2**- Assign each fuzzy subset with a linguistic label after dividing the entire discourse domain that each variable encompasses into a number of subsets. The universe's constituent elements are all represented in the subsets.
- **Step 3** - Get the membership function for each fuzzy subset.
- **Step 4** - To create the rule base, assign the fuzzy relationships between the inputs or states of the fuzzy subsets on one side and the output of the fuzzy subsets on the other side.
- **Step 5** - Choose appropriate range for input and output variable.

Table 5.2: Rule for speed control.

ce / e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Table 5.3: Rule for active damping control.

ce / e	NE	ZE	PE
NE	NE	NE	ZE
ZE	NE	ZE	PE
PE	ZE	PE	PE

- **Step 6** - Convert crisp input to fuzzy set by using fuzzification.
- **Step 7** - Using fuzzy approximation reasoning, determine the output that was contributed by each rule.
- **Step 8** - Combine the fuzzy results from each rule.
- **Step 9** - Crisp output is obtained from the fuzzy set by using defuzzification.

Fuzzy rule for speed control is represented in Table 5.2. Here, the output of the fuzzy logic controller is reference current, and the inputs are error and change in error. The difference between the reference speed and the actual speed of a master motor is the error in speed control. The difference between the speed of the slave motor and the speed of the master motor is the error in active damping control. The difference between the current error and the prior error is referred to as the change in error. The range of acceptable error in speed control can be defined as [-1000 1000]. The range of change in error is set to [-150 150]. The range of the reference current is described as being between [-200 200].

Table 5.3 indicates fuzzy rule base for active damping control. Here the range of error is $[-1000 \ 1000]$ and the range of change in error is $[-200 \ 200]$. $[-400 \ 400]$ is chosen as the range for reference current. The linguistic terms Negative error, Zero error, and Positive error are used to quantize the fuzzy input variables and output variables that is error, change in error and change in reference current respectively. The labels Negative Big, Negative medium, Negative small, Zero, Positive small, Positive medium and Positive Big are used to quantify the fuzzy input and output variable in speed control. Here the rules are expressed as IF-THEN expressions. There are 49 rules for speed control and 9 rules for active damping control. According to their preference and experience, the designer can select from a wide variety of forms to define the fuzzy membership function. Triangular and trapezoidal forms are common because they are simple to convey the concepts of designers and take less time to compute. Therefore, here triangular membership functions are employed.

The main disadvantage of fuzzy logic controller during parameter variation it doesnot provide good transient response.

5.4 Sliding Mode Controller

Sliding mode controller (SMC) is a well-known robust control technique that may ensure excellent tracking even when the system is subject to internal parameter fluctuations and outside disturbances. SMC is notable for its great precision and simplicity in addition to these other qualities. This chapter deals with the designing of sliding mode controller for dual PMSM.

Sliding mode controller is a non linear control strategy for maintaining stability and consistent performance in the face of modeling imprecision. SMC is mainly composed of two modes. first one is reaching phase and second one is sliding phase which is represented in Fig. 5.3.

Each feedback path's gains alternate between two values in accordance with a rule that is based on the state's value at any given time. The switching control rule is designed to direct the nonlinear plant's state trajectory onto a predetermined (user-selected) surface in the state space and retain it there for a subsequent period of time. The area is known as a switching surface. If the plant state trajectory rises "above" the surface, a feedback path has one gain; if it descends "below," a different gain. The proper switching protocol is defined by this surface.

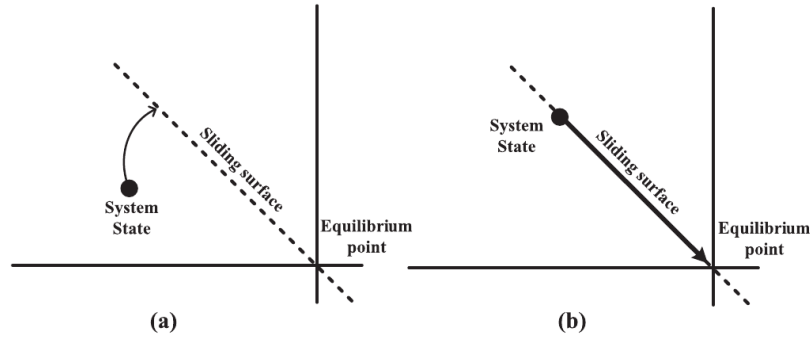


Figure 5.3: (a) Reaching Phase (b) Sliding Phase[24]

A sliding surface (sliding manifold) is another name for this area. In an ideal situation, after being intercepted, the switched control keeps the plant's state trajectory on the surface for the duration of the subsequent period, and the trajectory slides along the surface. The most crucial challenge is to create a switched control that will move the plant state to the switching surface and keep it there when it is intercepted. To describe this problem, a Lyapunov technique is used.

Two steps make up the controller design process. To confirm the sliding condition, a feedback control law is first chosen. The control law must, however, be discontinuous over the sliding surface in order to take modelling uncertainty and disturbances into account. Chattering results from an incorrect implementation of the associated control switching, which is undesirable in practice because it demands high control activity and may ignite high-frequency dynamics that were overlooked during modelling. As a result, the discontinuous control law is adequately smoothed in a subsequent step to provide the best possible trade-off between control bandwidth and tracking accuracy.

In the first step, robustness against parametric uncertainty is attained; in the second, robustness against high-frequency unmodelled dynamics is achieved. Chattering is reduced by removing the control discontinuity in a thin boundary layer adjacent to the switching surface.

5.4.1 SMC Design

Basic mechanical speed equation for dual PMSM is represented as

$$J \frac{d\omega_{r1,2}}{dt} + B\omega_{r1,2} = \frac{P}{2} T_{e1,2} \quad (5.2)$$

Motor torque equation

$$T_{e1,2} = \frac{3P}{2} \phi_f i_{q1,2} \quad (5.3)$$

From 5.2 we get the speed difference between two motors. ie,

$$\frac{d\Delta\omega_r}{dt} = -\frac{B}{J}\Delta\omega_r + \frac{1}{J}\frac{P}{2}(T_{e2} - T_{e1}) \quad (5.4)$$

Substitute equation 5.3 in 5.2 and 5.4 and obtain the state equation for dual PMSM which is expressed as

$$\begin{bmatrix} \dot{\omega}_{r1} \\ \Delta\dot{\omega}_r \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & 0 \\ 0 & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} \omega_{r1} \\ \Delta\omega_r \end{bmatrix} + \begin{bmatrix} \frac{3P^2\phi_f}{8J} & 0 \\ -\frac{3P^2\phi_f}{8J} & \frac{3P^2\phi_f}{8J} \end{bmatrix} \begin{bmatrix} i_{q1} \\ i_{q2} \end{bmatrix} \quad (5.5)$$

By using this state equation obtaining sliding surface, reaching law, and control law are briefly described as follows:

To apply the SMC to (5.5), first, calculate the sliding surfaces. Here sliding surfaces are chosen as

$$\begin{bmatrix} s_1 \\ s_2 \end{bmatrix} = \begin{bmatrix} e_1 + k_1 \int e_1 dt \\ e_2 + k_2 \int e_2 dt \end{bmatrix} \quad (5.6)$$

where s_1 is the sliding surface for speed controller and s_2 represents the sliding surface for active damping controller. e_1 is the difference between actual speed of master motor and reference speed ($e_1 = \omega_{r1} - \omega_{r1}^*$). e_2 indicates the difference between the two motors' speed errors ($e_2 = \Delta\omega_r - \Delta\omega_r^*$).

Next step is to design a reaching law that is required for the system's state to approach the sliding surfaces in (5.6).

The reaching law can be chosen as follows:

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = \begin{bmatrix} -k_3 \text{sgn}(s_1) - k_5 s_1 \\ -k_4 \text{sgn}(s_2) \end{bmatrix} \quad (5.7)$$

where the definition of the sgn function is

$$\text{sgn}(s) = \begin{cases} 1 & (s > 0) \\ 0 & (s = 0) \\ -1 & (s < 0) \end{cases} \quad (5.8)$$

where k_3 and k_4 stand for the corresponding sgn function gains for speed control and damping control. The sgn function and an extra term of $-k_5$ are the components of the reaching law of the master motor's speed controller. The quantity of chattering and the rate at which the system's state reaches the sliding surface depends on the value of k_3 if the reaching law is specified merely using the sgn function without the sliding surface. If k_3 is high, the time to the sliding surface is quick, but at a steady-state, there is a strong chattering phenomenon. The chattering reduces but the quickness of reaction slows down if k_3 is low. The speed difference between the two motors quickly converges to zero, although id1 chatters when the damping gain k_4 is high. On the other hand, chattering does not happen when k_4 is low, although the speed difference eventually approaches zero. This makes the additional term, k_5 , in (5.7) essential for enhancing the response of speed. The hyperbolic tangent is used in place of the sgn function to further minimize chattering (5.7). The reaching rule is then changed as follows:

$$\begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} = \begin{bmatrix} -k_3 \tanh(s_1) - k_5 s_1 \\ -k_4 \tanh(s_2) \end{bmatrix} \quad (5.9)$$

Substitute (5.5) into the derivative of (5.6) and it is equated to (5.7), the control law for SMC is obtained as

$$\begin{aligned} \begin{bmatrix} \dot{i}_q^* \\ \dot{i}_{q2}^* \end{bmatrix} &= \begin{bmatrix} \frac{8B}{3P^2\phi_f} & 0 \\ \frac{8B}{3P^2\phi_f} & \frac{8B}{3P^2\phi_f} \end{bmatrix} \begin{bmatrix} \omega_{r1} \\ \Delta\omega_r \end{bmatrix} \\ &+ \begin{bmatrix} -\frac{8J}{3P^2\phi_f} (k_1 e_1 - \dot{\omega}_{r1}^*) \\ -\frac{8J}{3P^2\phi_f} (k_1 e_1 + k_2 e_2 - \dot{\omega}_{r1}^*) \end{bmatrix} - \begin{bmatrix} k_3 \tanh(s_1) + k_5 s_1 \\ k_4 \tanh(s_2) \end{bmatrix} \end{aligned} \quad (5.10)$$

To investigate the existence condition, the Lyapunov function is frequently utilised here. The system reaches asymptotic stability when this criterion is met. In this work, the existence condition is verified in accordance with (5.6) and (5.7).

$$\begin{aligned} \frac{dW}{dt} &= \begin{bmatrix} s_1 & s_2 \end{bmatrix} \begin{bmatrix} \dot{s}_1 \\ \dot{s}_2 \end{bmatrix} \\ &= -k_3 s_1 \operatorname{sgn}(s_1) - k_5 s_1^2 - k_4 s_2 \operatorname{sgn}(s_2) \end{aligned} \quad (5.11)$$

In case k_3 , k_4 , and k_5 are chosen with positive values, the Lyapunov function in (7.10) will always be negative. The existence requirement is therefore satisfied.

Table 5.4: Gain values for SMC controller

	Without parameter variation	With parameter variation
Without active damping control	$K_1 = 50$ $K_3 = 1.25$ $K_5 = 0.7$	$K_1 = 10$ $K_3 = 1.4$ $K_5 = 0.8$
With active damping control	$K_2 = 0.1$ $K_4 = 80$	$K_2 = 0.12$ $K_4 = 10$

Table 5.4 represents the gain values of SMC for speed and active damping control. By the analysis of open loop response it is inferred that a small variation in system parameter leads to a large variation in system performance. So to compensate this problem a robust sliding mode controller is designed. But the main limitation of this control is chattering phenomenon. Therefore, to reduce this chattering a novel fuzzy sliding mode speed controller is designed.

5.5 Novel Fuzzy-Sliding Mode Controller

The Fuzzy Sliding Mode Controller (FSMC) combines the Sliding Mode Control algorithm (SMC) with a Fuzzy Logic Control (FLC) method.

The ability of the sliding mode control algorithm to provide strong transient performance and system robustness is well established. However, these performances have a few drawbacks: the emergence of the chattering phenomena brought on by the discontinuous part of the control, which can be damaging to the motors; the system is constantly under high control to assure its

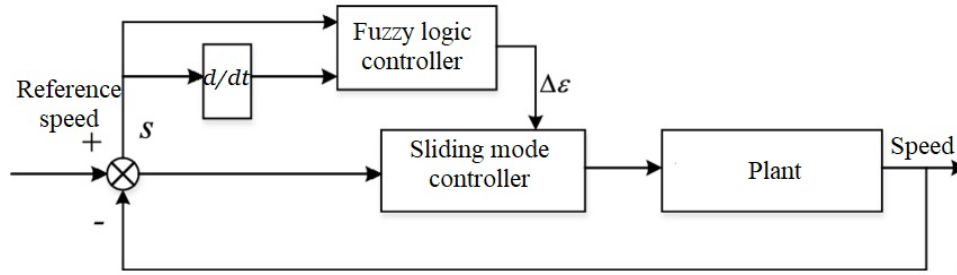


Figure 5.4: Basic structure of Fuzzy Sliding Mode Controller

convergence to the target state, and this is undesirable. Consequently, a fuzzy controller must be added to the sliding mode control in order to get a reliable and smooth control.

In this work, FSMC is mainly used to tune the switching gain in the control law to the variation in the error signal and the rate of change of the error signal, the performance of the sliding mode controller may be enhanced. The fuzzy system is given the sliding surface signal s and its rate of change \dot{s} as input, and its output is the value of k . Here SMC is designed by using the same procedure described in section (5.4).

Table 5.5: Fuzzy rule for tuning parameter

	NL	NM	ZE	PM	PL
$s\dot{s}$	NL	NM	ZE	PM	PL
k	NL	NM	ZE	PM	PL

Table 5.5 indicates the fuzzy rule for FSMC. There are 5 rules for tune the switching gain and it is expressed as IF-THEN expressions. Negative large, Negative medium, Zero, Positive medium and Positive large are the linguistic labels used here and triangular membership functions are employed for easy computation. The range of input and output fuzzy set for speed control is $[-1.5 \ 1.5]$. In active damping control the range of input and output fuzzy set is $[-150 \ 150]$, $[-100 \ 100]$ respectively.

5.6 Concluding Remarks

This chapter focuses on the overall design of the various controllers (PI, Fuzzy, SMC, and Fuzzy-SMC) to ensure the stable operation of a dual PMSM. It also discusses the rules governing fuzzy controllers and the control law for SMC.

Chapter 6

RESULTS AND DISCUSSION

6.1 Overview

In this chapter, the efficiency of several speed control strategies such as PI, Fuzzy, SMC, and Fuzzy-SMC is validated using simulations to analyse system performance with and without parameter variation.

6.2 Load Torque Characteristics

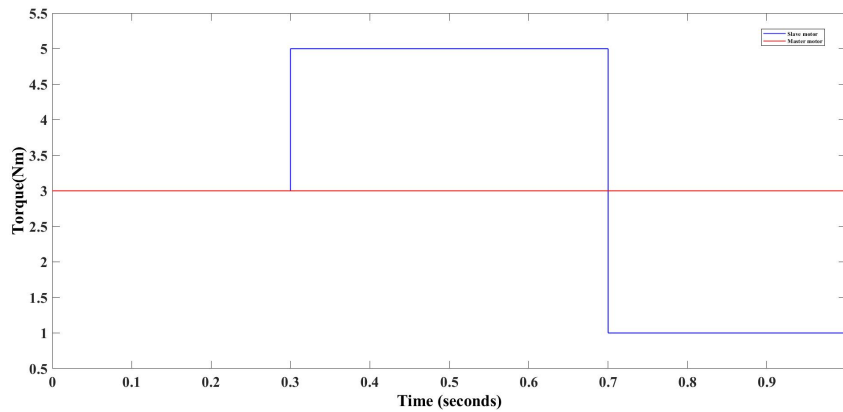


Figure 6.1: Load torque variation

The load torque applied to both motors is shown in Fig 6.1. The load torque of the master and slave motors is indicated by the red and blue lines respectively. The figure shows that the load torque of the master motor is constant, but that of the slave motor changes between 0.3 and 1 second. During the time-frame 0.3 second to 0.7 second, the slave motor's load torque

exceeds that of the master motor. This causes large oscillations in the slave motor. In order to suppress these oscillation, various speed controller with active damping control is implemented.

6.3 PI Controller

Simulation results using the PI controller with and without active damping control are discussed in the following sections. From the analysis of a system model, it is inferred that a small variation in system parameters leads to a large variation in system performance. As a result, the controller's performance is evaluated by varying the system parameters.

6.3.1 Speed Response-Without Parameter Variation

(i) Without Active Damping Control

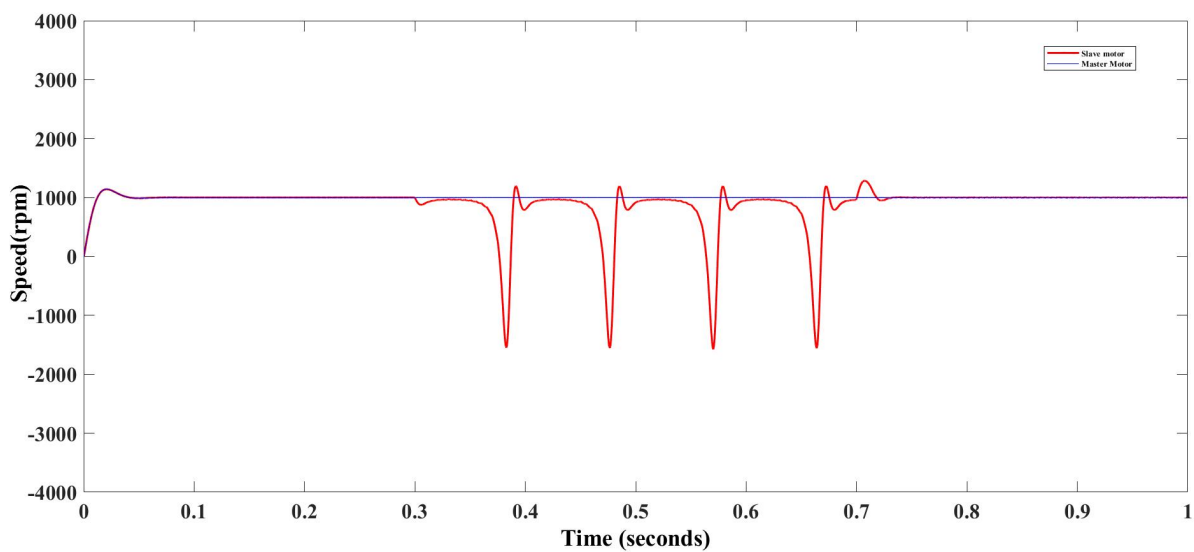


Figure 6.2: Dual PMSM speed response using PI controller without active damping

Fig. 6.2 depicts the speed characteristics of a dual PMSM with a PI controller but no active damping. The reference speed of 1000 rpm is achieved here, although oscillations occur in the slave motor from 0.3s to 0.7s owing to load torque fluctuation.

(ii) With Active Damping Control

Active damping control is used along with speed control to prevent oscillations. The simulation result employing a PI controller with active damping is shown in Fig 6.3. When compared to the outcome of PI without active damping, the oscillations are minimized and it settles faster.

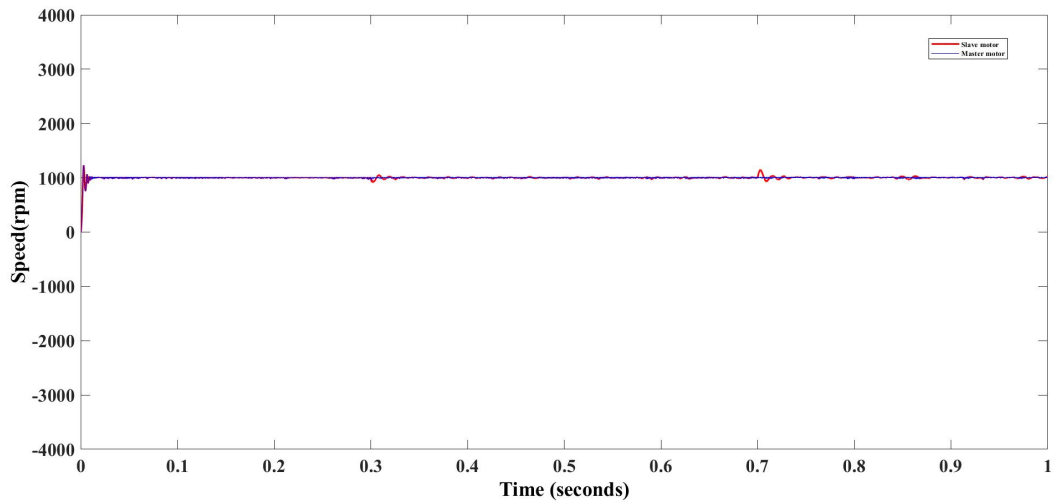


Figure 6.3: Dual PMSM speed response using PI controller with active damping

6.3.2 Speed Response-With Parameter Variation

(i) Without Active Damping Control

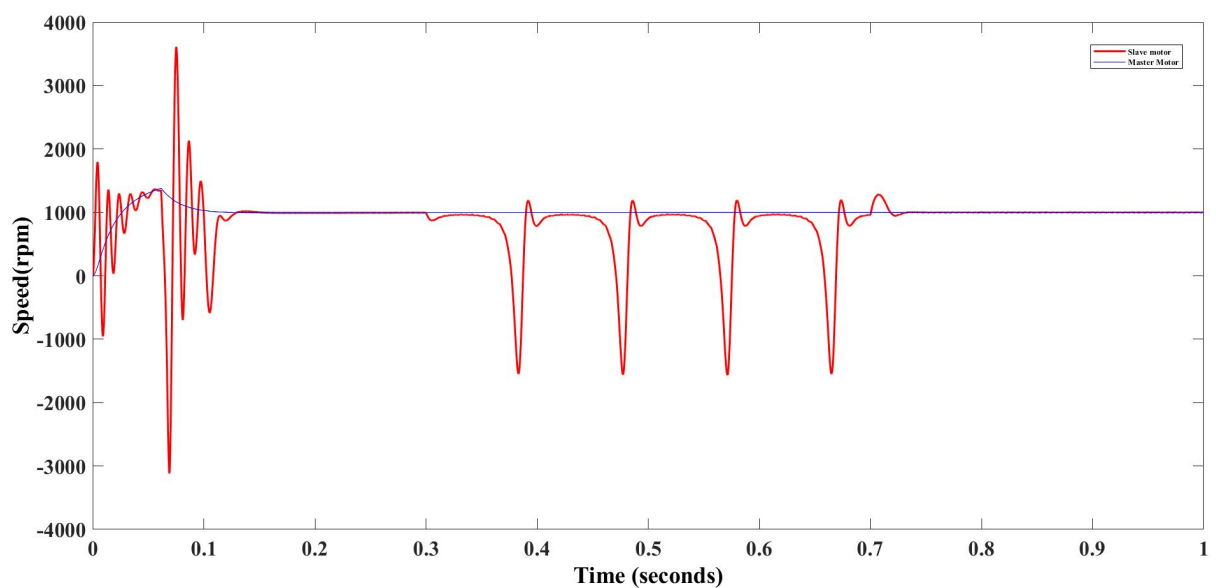


Figure 6.4: Dual PMSM speed response using PI controller without active damping (when the parameter is varied)

The controller's efficiency is validated for evaluating performance by varying the system parameter. Fig. 6.4 depicts the speed response of dual PMSM without active damping with parameter variation. In this characteristics, the transient response is poor when comparing with PI controller without parameter fluctuation, and there is greater oscillation.

(ii) With Active Damping Control

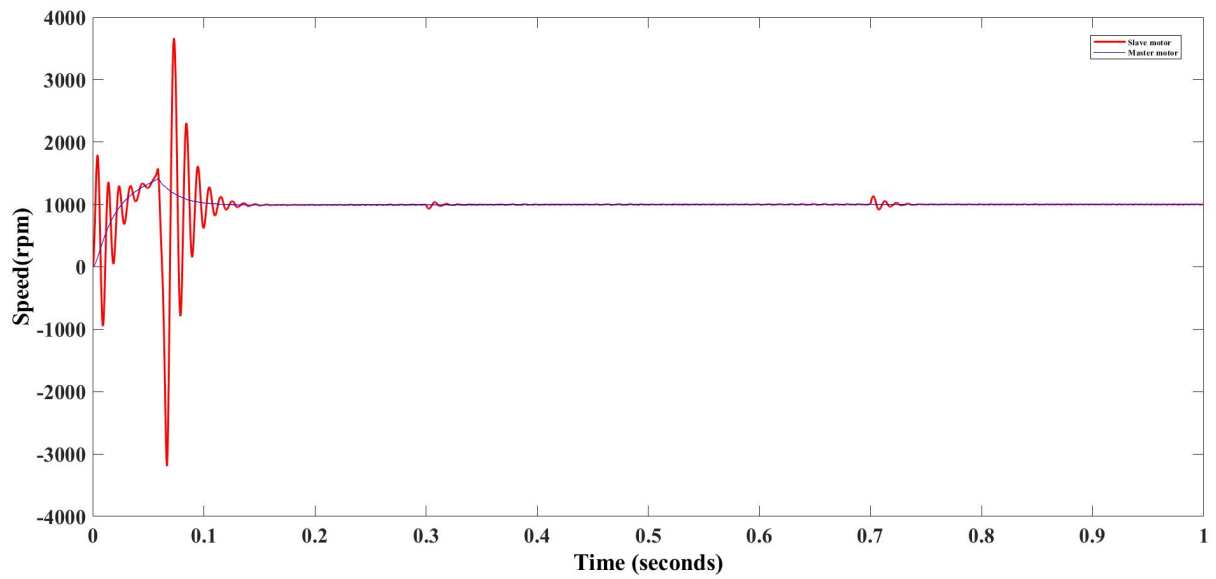


Figure 6.5: Dual PMSM speed response using PI controller with active damping (when the parameter is varied)

Fig. 6.5 depicts the speed response of a dual PMSM with active damping as the parameters are varied. To some extent, a PI controller with active damping can suppress the oscillation.

6.3.3 Results and Discussion

Table 6.1 indicates the performance of dual PMSM by using PI controller with and without parameter variation. In without parameter variation with active damping control the speed achieve reference speed at 0.02 s and with parameter variation it settled at 0.149 s.

Table 6.1: Settling time of dual PMSM by using PI controller with and without parameter variation

	Without parameter variation	With parameter variation
Without active damping control	Settling time = 0.066s	Settling time = 0.153s
With active damping control	Settling time= 0.02s	Settling time= 0.149s

6.4 Fuzzy Logic Controller

Simulation results obtained with and without active damping control using the fuzzy logic controller are discussed in the following sections

6.4.1 Speed Response-Without Parameter Variation

(i) Without Active Damping Control

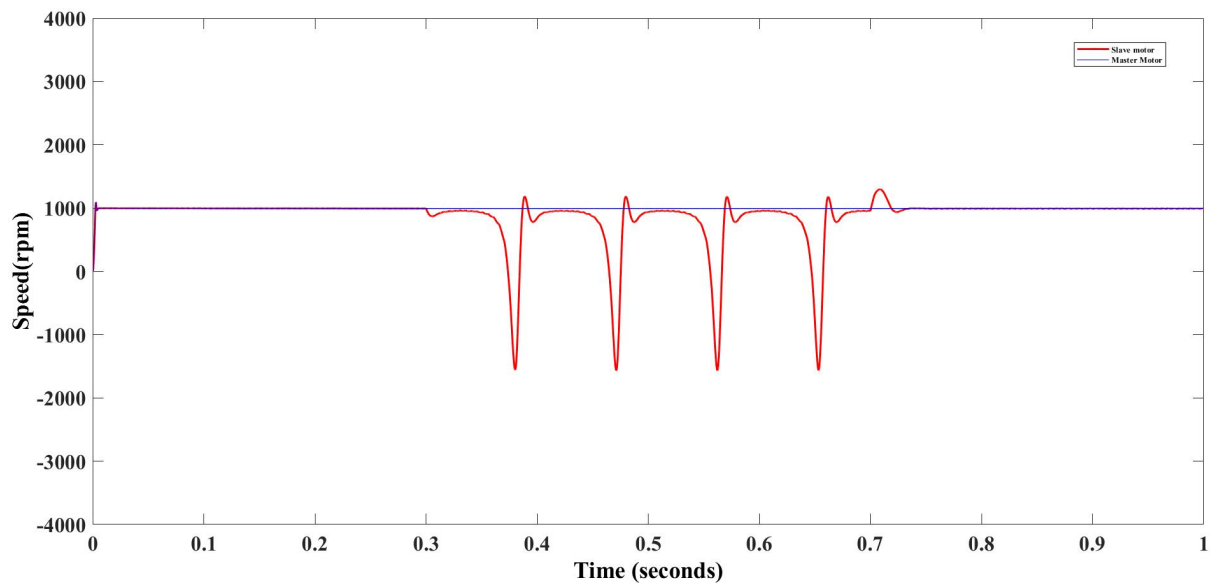


Figure 6.6: Dual PMSM speed response using fuzzy logic controller without active damping

The speed characteristics of a dual PMSM with a fuzzy logic controller but no active damping are shown in Figure 6.6. In this characteristics, the transient response of dual PMSM by

using fuzzy logic controller is better as compared with PI controller. But also oscillations are occurred in the slave motor from 0.3second to 0.7second due to load torque variation.

(ii) With Active Damping Control

To prevent oscillations, active damping control is utilized along with speed control. Fig. 6.7 depicts the simulation result using a fuzzy logic controller with active damping. In comparison to the result of PI with active damping, the oscillations are suppressed better in the absence of parameter variation, and it settles at 0.02 second.

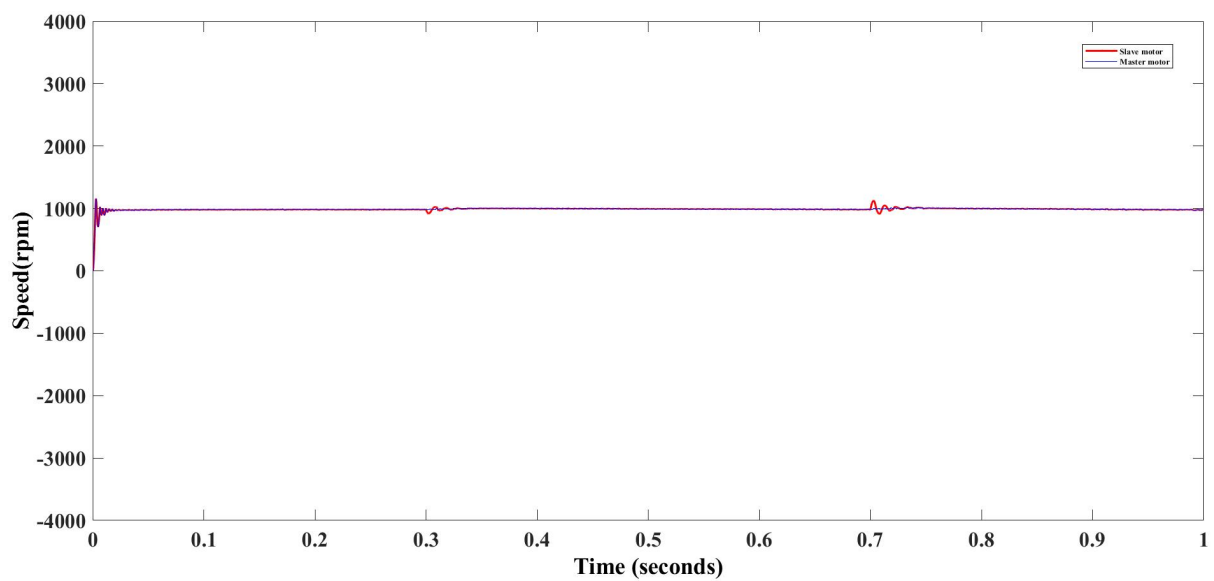


Figure 6.7: Dual PMSM speed response using fuzzy logic controller with active damping

6.4.2 Speed Response-With Parameter Variation

(i) Without Active Damping Control

By varying the moment of inertia, the controller's efficiency is validated for performance evaluation. The speed response of a dual PMSM without active damping with parameter variation is depicted in Figure 6.8. When compared to the PI controller, it have better settling time ie, 0.07 second.

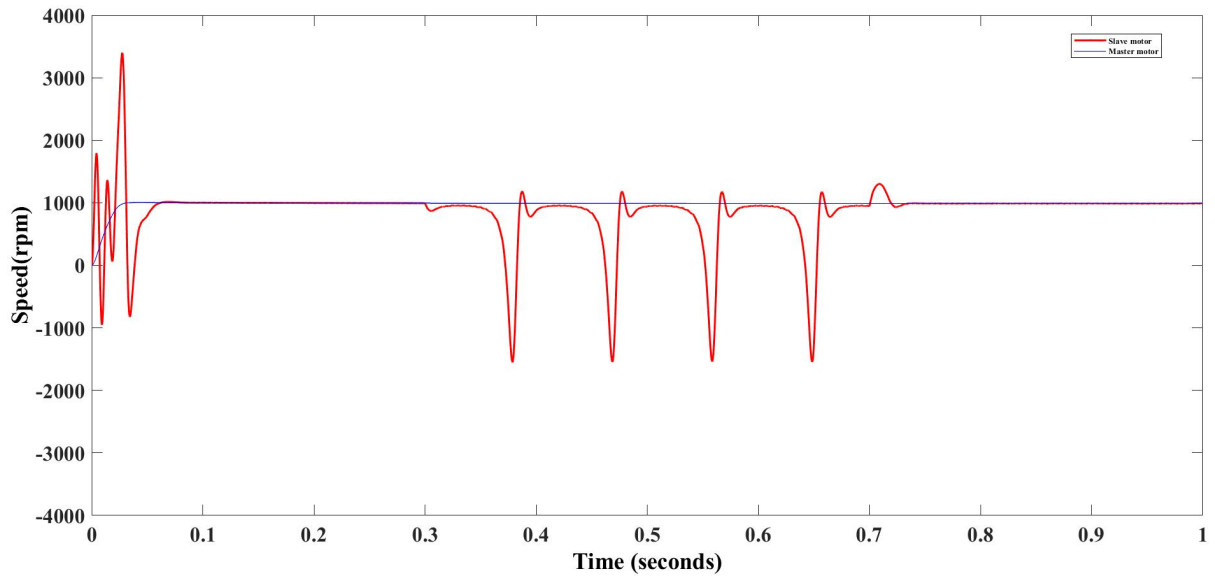


Figure 6.8: Dual PMSM speed response using Fuzzy logic Controller without active damping (when the parameter is varied)

(ii) With Active Damping Control

The speed response of a dual PMSM with active damping is shown in Fig 6.9 as the parameters are varied. The transient response is better to that of the PI controller. But it totally cannot suppress the oscillations. The settling time of this response is 0.062 seconds.

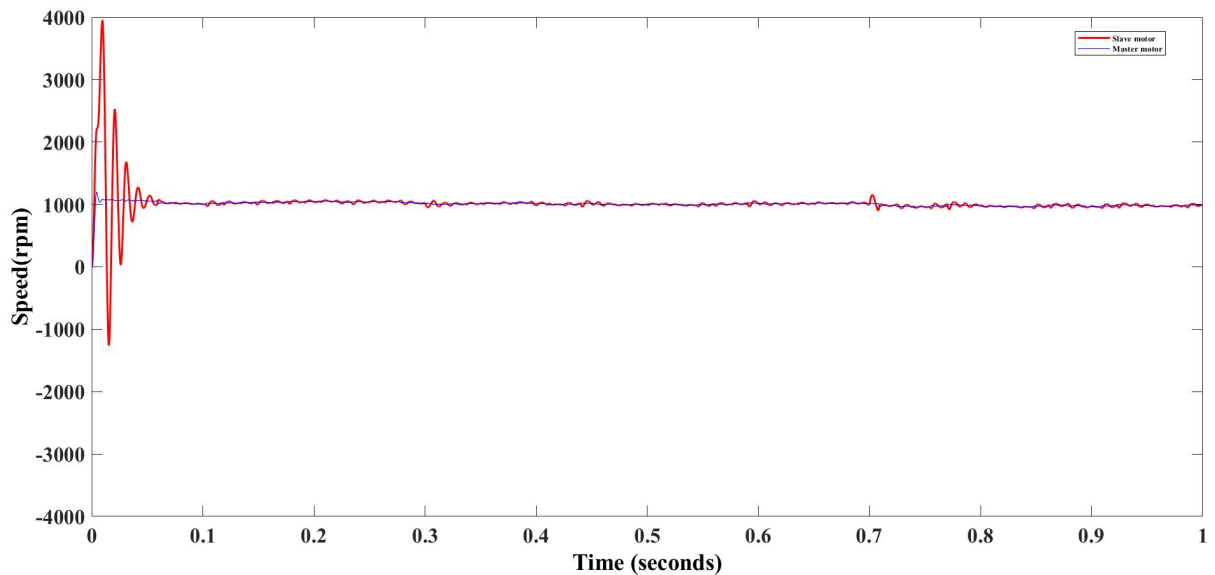


Figure 6.9: Dual PMSM speed response using Fuzzy logic Controller with active damping (when the parameter is varied)

6.4.3 Results and Discussion

Table 6.2: Settling time of dual PMSM using fuzzy logic controller with and without parameter variation

	Without parameter variation	With parameter variation
Without active damping control	Settling time = 0.00638s	Settling time = 0.07s
With active damping control	Settling time= 0.02s	Settling time= 0.062s

6.5 Sliding Mode Controller

The simulation results achieved with and without active damping control using the Sliding mode controller is represented in below section.

6.5.1 Speed Response-Without Parameter Variation

(i) Without Active Damping Control

Fig 6.10 represents the speed characteristics of a dual PMSM with a sliding mode controller but no active damping. Settling time of dual PMSM by using SMC is much less than that of a PI controller. However, as compared to the fuzzy logic controller, it takes some time to reach the reference speed. Due to load torque variation, oscillations occurred in slave motor ranging from 0.3s to 0.7s.

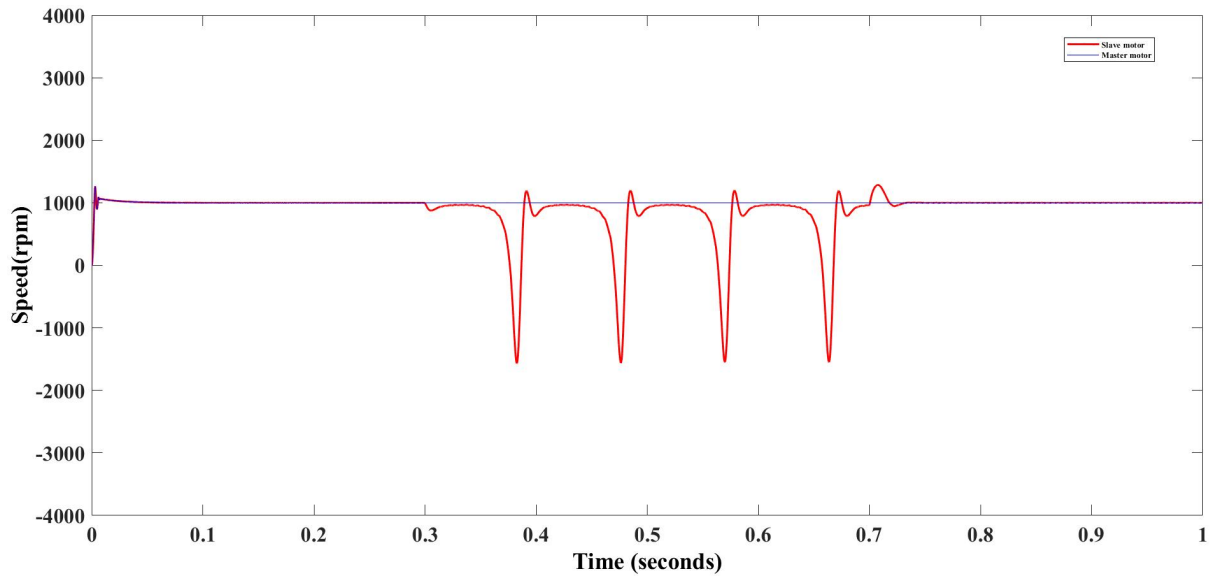


Figure 6.10: Dual PMSM speed response using sliding mode controller without active damping

(ii) With Active Damping Control

The simulation results employing a sliding mode controller with active damping is shown in Fig. 6.11. Here the settling time of speed response using SMC and fuzzy is same.

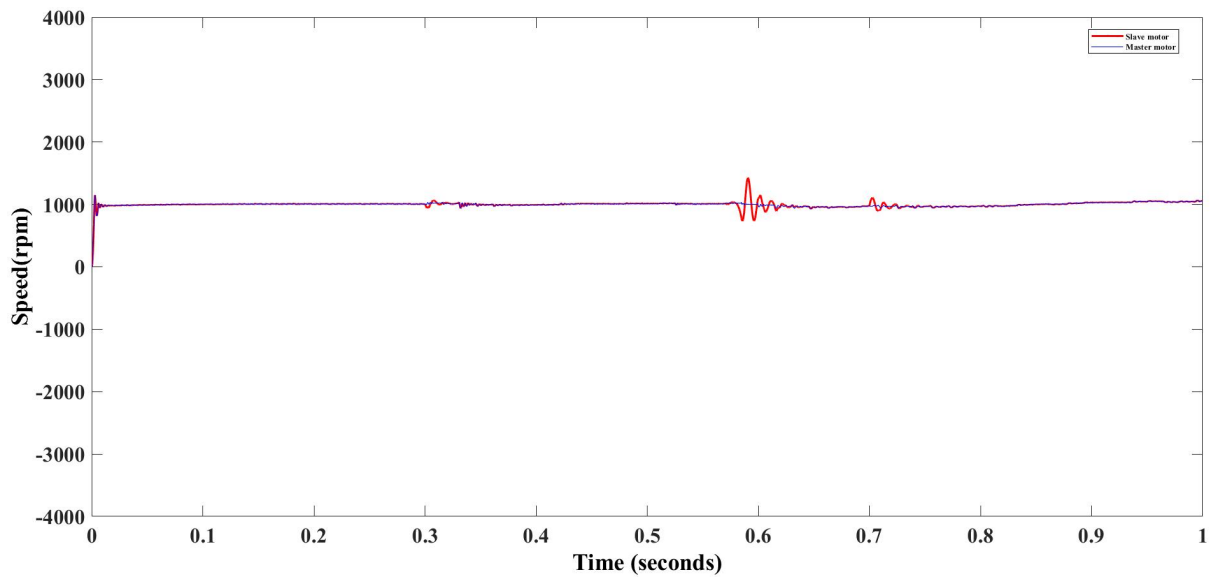


Figure 6.11: Dual PMSM speed response using sliding mode controller with active damping

6.5.2 Speed Response-With Parameter Variation

(i) Without Active Damping Control

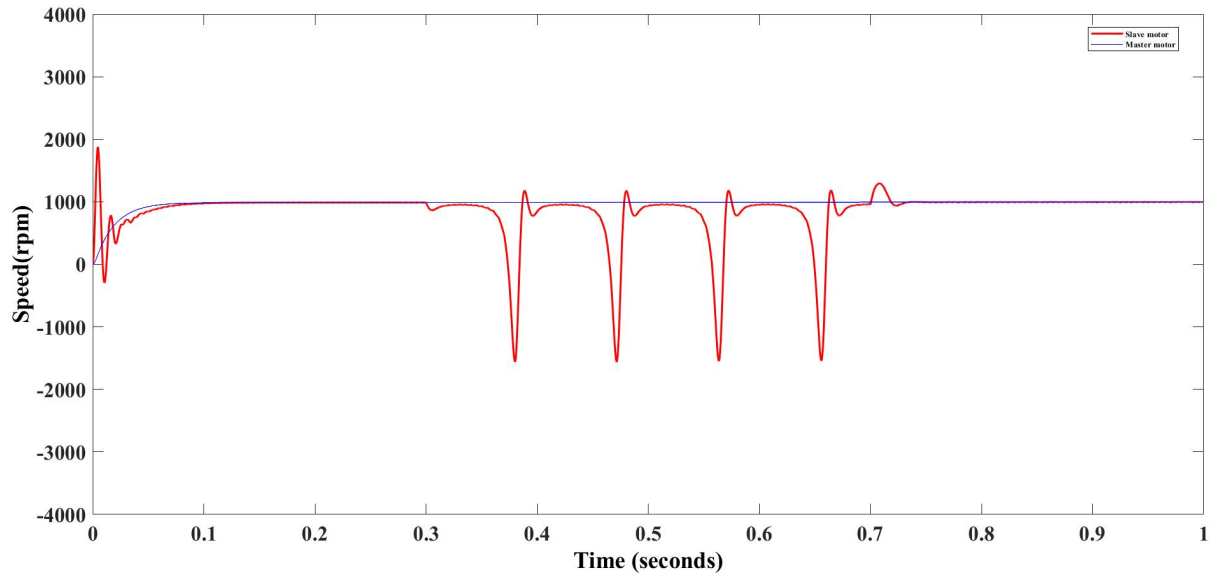


Figure 6.12: Dual PMSM speed response using Sliding mode Controller without active damping (when the parameter is varied)

Fig. 6.12 depicts the speed response of dual PMSM without active damping with parameter variation. In this response, as compared with PI and fuzzy, its transient response and settling time is better.

(ii) With Active Damping Control

Fig 6.13 represents the speed characteristics of a dual PMSM with active damping during parameter variation. SMC provides a better transient response and achieves reference speed faster as compared with PI and Fuzzy.

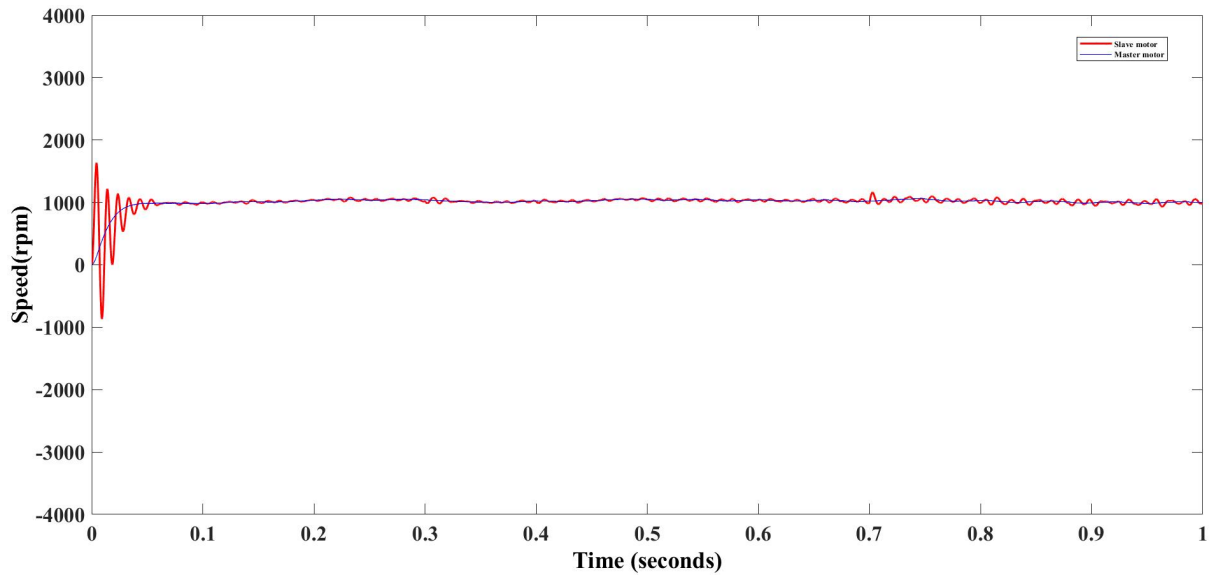


Figure 6.13: Dual PMSM speed response using Sliding mode Controller with active damping(when the parameter is varied)

6.5.3 Results and Discussion

Table 6.3: Settling time of dual PMSM by using Sliding mode controller with and without parameter variation

	Without parameter variation	With parameter variation
Without active damping control	Settling time = 0.047s	Settling time = 0.069s
With active damping control	Settling time= 0.022s	Settling time= 0.06s

6.6 Novel Fuzzy-Sliding Mode Controller

Simulation results using the Fuzzy-Sliding mode controller with and without active damping control are discussed in the following sections.

6.6.1 Speed Response-Without Parameter Variation

(i) Without Active Damping Control

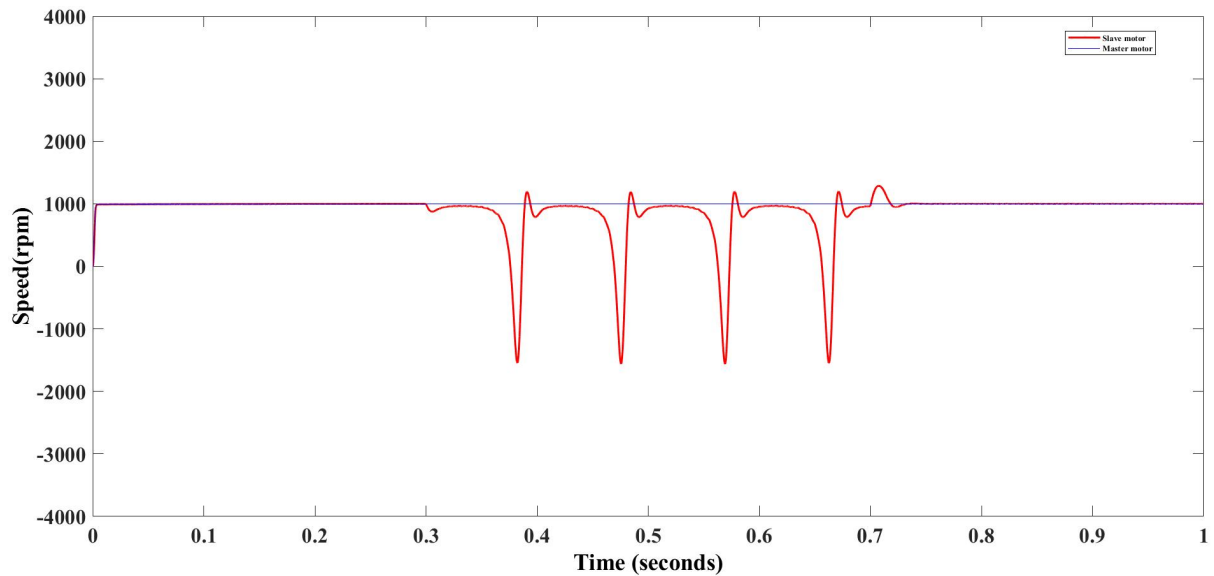


Figure 6.14: Dual PMSM speed response using Fuzzy-Sliding mode Controller without active damping

Fig. 6.14 displays the speed characteristics of a dual PMSM with a Fuzzy-Sliding mode controller but no active damping. When compared to previous control schemes, this control technique achieves the reference speed of 1000 rpm with less settling time with no peak overshoot. But oscillations are occurred in the slave motor between 0.3s to 0.7s due to the variation in load torque. So active damping control is necessary to suppress the unwanted oscillation.

(ii) With Active Damping Control

To prevent oscillations, active damping control is used along with speed control. Fig. 6.15 depicts the simulation result using a Fuzzy-Sliding mode controller with active damping. When compared to the results of previous control schemes, the Fuzzy Sliding Mode Controller suppress the oscillation and it has fast response.

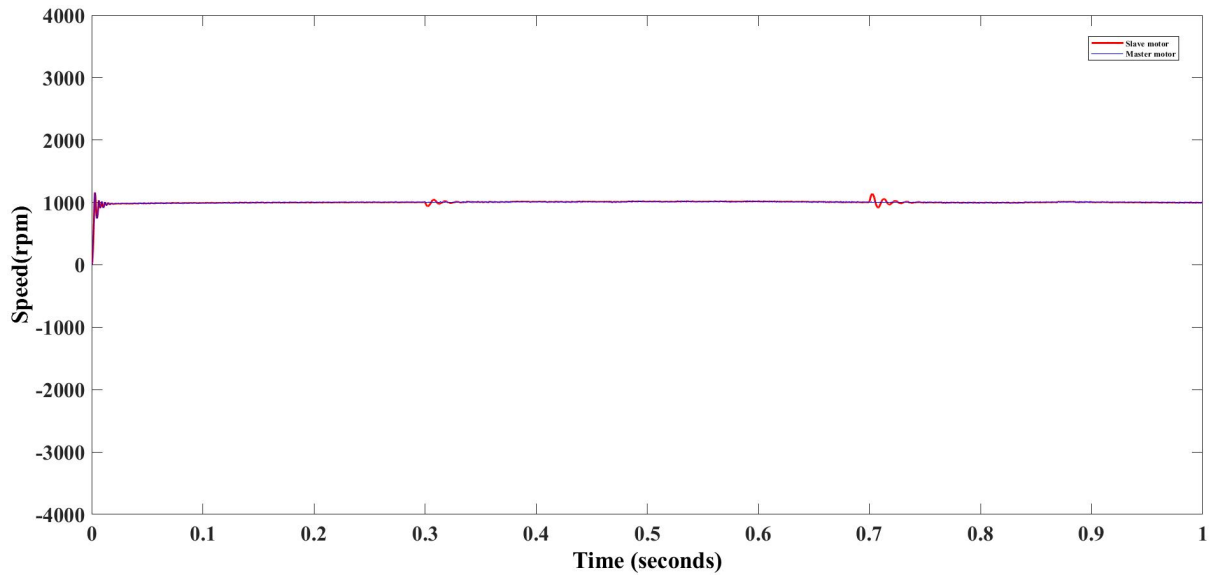


Figure 6.15: Dual PMSM speed response using Fuzzy-Sliding mode Controller with active damping

6.6.2 Speed Response-With Parameter Variation

(i) Without Active Damping Control

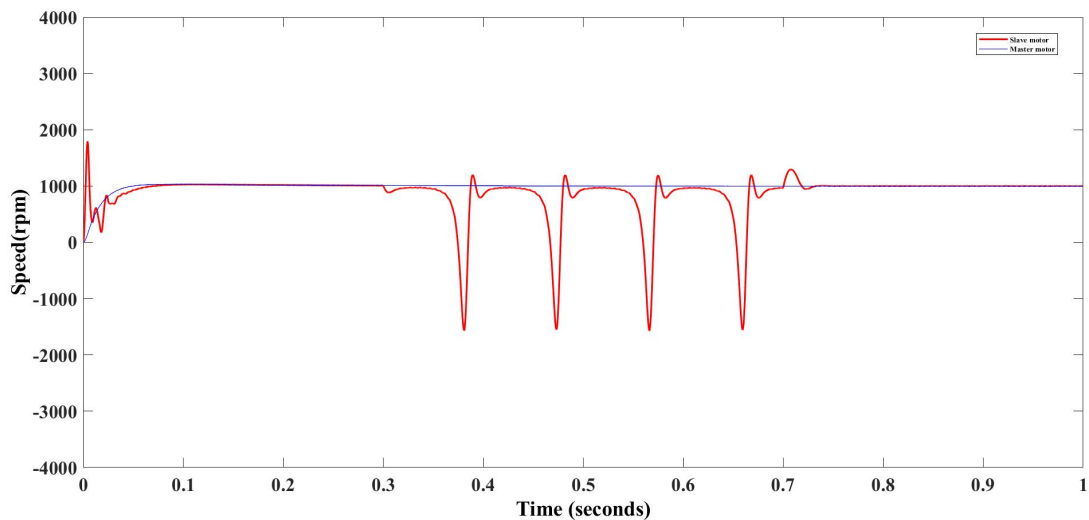


Figure 6.16: Dual PMSM speed response using Fuzzy-Sliding mode Controller without active damping (when the parameter is varied)

The controller's efficiency is tested for performance evaluation by changing the moment of inertia. Fig. 6.16 depicts the speed response of a dual PMSM without active damping with parameter variation. This response achieves reference speed much faster than conventional control strategies such as PI, fuzzy, and SMC.

(ii) With Active Damping Control

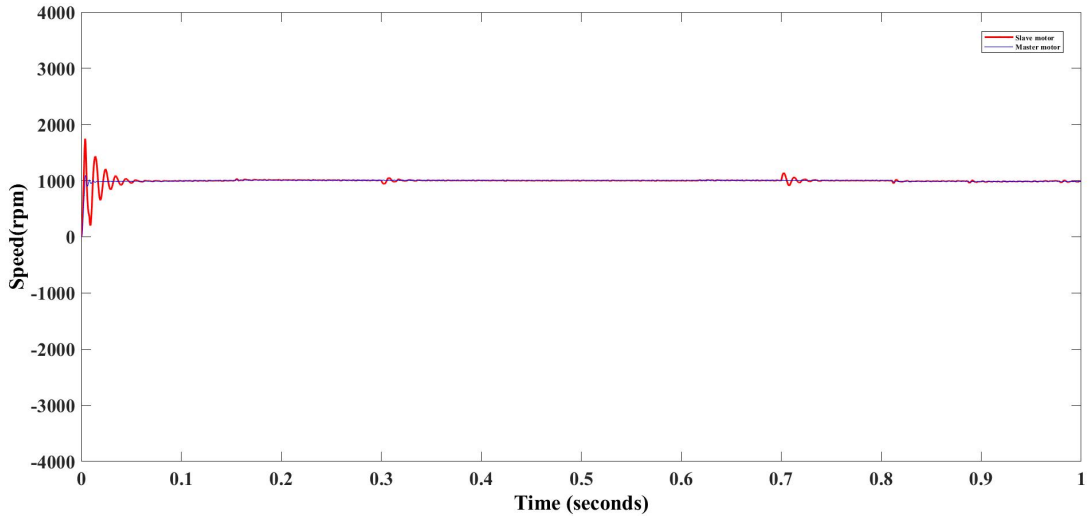


Figure 6.17: Dual PMSM speed response using Fuzzy-Sliding mode Controller with active damping(when the parameter is varied)

The speed response of a dual PMSM with active damping is shown in Fig. 6.17 as the parameters are varied. In this characteristics, transient response and settling time are better as compared to previous control strategies such as PI, Fuzzy and SMC.

6.6.3 Results and Discussion

Table 6.4: Settling time of dual PMSM by using Fuzzy-Sliding mode controller with and without parameter variation

	Without parameter variation	With parameter variation
Without active damping control	Settling time = 0.003694s	Settling time = 0.067s
With active damping control	Settling time= 0.016s	Settling time= 0.054s

6.7 Overall Comparison of Controllers With and Without Parameter Variation

Table 6.5: Settling time of dual PMSM by using different controllers without parameter variation

	SETTLING TIME			
	PI	FUZZY	SMC	FUZZY-SMC
Without acting damping control	0.066s	0.00638s	0.047s	0.003694s
With active damping control	0.02s	0.022s	0.022s	0.016s

Table 6.6: Settling time of dual PMSM by using different controllers with parameter variation

	SETTLING TIME			
	PI	FUZZY	SMC	FUZZY-SMC
Without acting damping control	0.153s	0.07s	0.069s	0.067s
With active damping control	0.149s	0.062s	0.06s	0.054s

6.8 Concluding Remarks

This chapter deals with validation and analysis of various controllers such as PI, Fuzzy, SMC and Novel Fuzzy-SMC; to achieve a solution for the problem defined. During parameter variation, the response of dual PMSM with PI controller is sluggish and it takes more time to settle down. So a linguistic rule based Fuzzy logic controller was implemented to improve the system performance rather than PI controller. From the analysis of this response, it is inferred that the system performance is improved on without parameter variation. But during parameter variation, the response provided by this controller is not much improved. Therefore a sliding mode controller is used to improve the system performance during parameter variation. The main limitation of this control is chattering phenomenon. Due to this problem, a novel Fuzzy Sliding mode controller is designed. As a result the transient response of dual PMSM is much better as compared to previous control techniques.

Chapter 7

CONCLUSION

In this work the literature review on dual permanent magnet synchronous motor has been carried out and mathematical model of the system is designed. In the open loop characteristics, system achieve rated speed at a rated torque. By the analysis of system model, it is inferred that a small variation in system parameter leads to a large variation in system performance and also, during variable speed application it is necessary to achieve a desired speed other than rated speed. So a speed controller is essential for dual PMSM to track the reference speed. Moreover, there is an oscillation occurred in the slave motor due to the variation in load torque. So various speed controller along with active damping control (PI, Fuzzy, SMC, Fuzzy-SMC) are designed here to analyse the system performance. By comparing results, it is found that the Fuzzy Sliding Mode Controller gives the best performance than PI, Fuzzy and SMC.

References

- [1] A. Balashanmugham and M. Maheswaran, "Permanent-Magnet Synchronous Machine Drives," in *Applied Electromechanical Devices and Machines for Electric Mobility Solutions*, IntechOpen, 2020.
- [2] Tseng, S.K., Tseng, C.C., Liu, T.H., Chen, J.L, "Wide range adjustable speed control method for dual-motor drive systems," *IET Electric Power Applications*, 2015.
- [3] S.Khaldoune, P.Maria, D.Abdelaziz, "Hardware in loop methodologies for the control of dual PMSM connected in parallel: FPGA implementation and experimentation," *European Conference on Power Electronics and Applications*, 2015.
- [4] A. Asri, D. Ishak, S. Iqbal, and M. Kamarol, "A speed sensorless field-oriented control of parallel-connected dual PMSM," *IEEE International Conference on Control System, Computing and Engineering*, 2011.
- [5] Ahmad Asri Abd Samat, D. Ishak, P. Saedin and S. Iqbal, "Speed- sensorless control of parallel-connected PMSM fed by a single inverter using MRAS," *IEEE International Power Engineering and Optimization Conference Melaka*, Malaysia, 2012.
- [6] K. Matsuse, H. Kawai, Y. Kouno, and J. Oikawa, "Characteristics of speed sensorless vector controlled dual induction motor drive connected in parallel fed by a single inverter," *IEEE Trans. Ind. Appl.*, vol.40, no.1, pp-153-161, 2004.
- [7] He, Y., Hu, W., Wang, Y., Wu, J., Wang, Z, "Speed and position sensorless control for dual three-phase PMSM drives", *IEEE Applied Power Electronics Conference and Exposition*, 2009.

- [8] J.-Q. Shen, L. Yuan, M.-L. Chen, and Z. Xie, "Flux sliding-mode observer design for sensorless control of dual three-phase interior permanent magnet synchronous motor," *J. Electr. Eng. Technol.*, vol. 9, no. 5, pp. 1614–1622, 2014.
- [9] L. Jurifa, I. Zulkiflie, S. Marizan, "Fuzzy logic speed controller with reduced rule base for dual PMSM drives", *International Science Index*, 2011.
- [10] L. R. Ramelan, E. Firmansyah, T. Liu, S. Tseng, and J. Hsu, "An improved maximum efficiency control for dual-motor drive systems," *International Conference on Information Technology and Electrical Engineering (ICITEE)*, 2014.
- [11] J. Zhang, X. -H. Wen and Y. -L. Wang, "Research on Optimized control technique of Electrical vehicles propulsion system with dual PMSM connection," *IEEE Energy Conversion Congress and Exposition*, 2011.
- [12] G. Brando, L. Piegari, and I. Spina, "Simplified optimum control method for mono inverter dual parallel PMSM drive," *IEEE Trans. Ind. Electron.*, vol. 65, no. 5, pp. 3763–3771, 2018.
- [13] T. Liu and M. Fadel, "An Efficiency-Optimal Control Method for Mono-Inverter Dual-PMSM Systems," in *IEEE Transactions on Industry Applications*, vol. 54, no. 2, pp. 1737-1745, 2018.
- [14] M. Cychowski, P. Serkies, R. Nalepa and K. Szabat, "Model predictive speed and vibration control of dual-inertia PMSM Drives," *2011 IEEE International Symposium on Industrial Electronics*, 2011.
- [15] N. L. Nguyen, M. Fadel, and A. Llor, "A new approach to Predictive Torque Control with Dual Parallel PMSM system," *2013 IEEE International Conference on Industrial Technology (ICIT)*, 2013.
- [16] Z. Xu, Z. Wang, X. Wang, and M. Cheng, "Predictive current control method for dual three-phase PMSM drives with reduced switching frequency and low computation burden," *IET electr. Power appl.*, vol. 14, no. 4, pp. 668-677, 2020.
- [17] S. Ye, "Fuzzy sliding mode observer with dual SOGI-FLL in sensorless control of PMSM drives," *ISA Trans.*, vol. 85, pp. 161–176, 2019.

- [18] X. Wang, Z. Wang and Z. Xu, "A Hybrid Direct Torque Control Scheme for Dual Three-Phase PMSM Drive With Improved Operation Performance," in *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1622-1634, Feb. 2019.
- [19] T. Kamel, D. Abdelkader, B. Said, S. Padmanaban, and A. Iqbal, "Extended Kalman filter based sliding mode control of parallel-connected two five-phase PMSM drive system," *Electronics (Basel)*, vol. 7, no. 2, p. 14, 2018.
- [20] Krishnan, R. "Permanent magnet synchronous and brushless DC motor drives", 2017.
- [21] S. Sakunthala, R. Kiranmayi, and P. N. Mandadi, "A study on industrial motor drives: Comparison and applications of PMSM and BLDC motor drives," *International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, 2017.
- [22] P. Thampi, C. Kiran "A review on controlling techniques for permanent magnet synchronous motor (PMSM) and current state of the art in the research area," *Communications on Applied Electronics*, 2019.
- [23] D. Bidart, M.P. David, P. Maussion, and M. Fadel, "Mono inverter multi parallel magnet synchronous motor: Structure and control strategy," *IET Elect. Power Appl*, vol.5, no.3, pp.1103-1108, Mar. 2001.
- [24] F. Mohd Zaihidee, S. Mekhilef, and M. Mubin, "Robust speed control of PMSM using sliding mode control (SMC)—A review," *Energies*, vol. 12, no. 9, p. 1669, 2019.
- [25] <https://images.app.goo.gl/mhYamn9e31JLCRbYA>
- [26] <https://images.app.goo.gl/B22hz2ScejEHFa7i6>
- [27] <https://images.app.goo.gl/quqMJRym4P3kE8JM9>
- [28] <https://images.app.goo.gl/HHkMdhPfHs1V22h38>
- [29] X. Zhang, Y. Cheng, Z. Zhao and K. Yan, "Optimized Model Predictive Control With Dead-Time Voltage Vector for PMSM Drives," in *IEEE Transactions on Power Electronics*, vol. 36, no. 3, pp. 3149-3158, March 2021.

List of Publications

- [1] Shahina S and Farsana Muhammed, "Review of Speed Controlling Techniques on Dual-PMSM Drive Systems," *International Conference on Futuristic technologies in Control systems Renewable energy (ICFCR)*, 2022 - Accepted
- [2] Shahina S and Farsana Muhammed, "Fuzzy-Sliding Mode Speed Controller with Active Damping Control for Dual-PMSM," *IEEE 19th India Council International Conference (INDICON)*, 2022 - Processing