DESIGN OF SERVODRIVE FOR ROBOTIC WELDING APPLICATIONS AND ANALYSIS WITH PI AND FUZZY LOGIC CONTROLLER

MANOJ KUMAR M

(22MQ02)

Dissertation submitted in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

Branch: ELECTRICAL AND ELECTRONICS ENGINEERING

Specialization: POWER ELECTRONICS AND DRIVES

of Anna University

MAY 2024

ELECTRICAL AND ELECTRONICS ENGINEERING

PSG COLLEGE OF TECHNOLOGY

(Autonomous Institution)

COIMBATORE – 641 004

PSG COLLEGE OF TECHNOLOGY

(Autonomous Institution)

COIMBATORE – 641 004

DESIGN OF SERVODRIVE FOR ROBOTIC WELDING APPLICATIONS AND ANALYSIS WITH PI AND FUZZY LOGIC CONTROLLER

Bonafide record of work done by

MANOJ KUMAR M

(22MQ02)

Dissertation submitted in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

Branch: ELECTRICAL & ELECTRONICS ENGINEERING

Specialization: POWER ELECTRONICS AND DRIVES

of Anna University

MAY 2024

....

Dr. M. Anand **Dr. J. Kanakaraj**

Faculty Guide Head of the Department

Certified that the candidate was examined in the vivavoce examination held on ....

....

(Internal Examiner) (External Examiner)

ACKNOWLEDGEMENT

I express my sincere thanks to **Dr. K. Prakasan, Principal**, PSG College of Technology, for providing the necessary support and opportunity to do this work.

I extend my profound gratitude to **Dr. J. Kanakaraj, Professor** and **Head of the Department**, Department of Electrical and Electronics Engineering, who has always been a source of inspiration and I thank him for the support and constant encouragement for doing the project.

I express my heartfelt thanks to **Dr. M. Anand, Assistant Professor (Sl. Gr.),** Department of Electrical and Electronics Engineering, Project Guide who has provided constant support throughout the project. I thank him for his patience and encouragement. His timely motivation at various stages of the work has greatly helped me in accomplishing the project. I am extremely fortunate for the wonderful experience I had while working with him.

My sincere thanks to our project committee members **Dr. L. Ashok Kumar, Professor** and **Dr. N. Archana, Assistant Professor (Sl. Gr.),** Department of Electrical and Electronics Engineering, for providing constant support and for guiding me during the project by reviewing the work progress.

I thank the Almighty and dedicate equal acknowledgments to all the student friends for their motivation, encouragement and continuous support for my project which helps for my successful completion.

I gratefully acknowledge my indebtedness to my parents without them I could not have achieved this height. I thank above all for their blessings showered on me to complete my project work.

TABLE OF CONTENTS

SYNOPSIS

In recent years, servomotor is widely used in variety of industries applications such as medical, robotics, manufacturing, welding and automotive etc. It is due to their high efficiency, lightweight, and low-cost advantages. Servomotors play a vital role in numerous industrial applications where precise control of position, velocity, and acceleration. Precise welding cannot be done repeatedly by humans, so the servodrives are implemented for the welding applications. Choosing a best control technique is necessary to effectively satisfy the needs of precise control, high efficiency, and quick reaction in servomotor applications.

Field-oriented control of a servomotor is a sophisticated control technique that enhances motor efficiency and independent control for optical performance by decoupling torque and flux components. The independent control of torque and flux, enhancing operational smoothness, and minimizing torque ripple is the primary aim of this project. The seamless integration is achieved by an architecture of optimized power electronics with a robust drive system.

The project is focused on the Field Oriented Control of servomotor drive system by means of PI and Fuzzy Logic Controllers in MATLAB/Simulink. The test results shows that using a fuzzy logic controller (FLC) for servo motor control has been found to be better than the traditional Proportional-Integral (PI) controller. It offers better control accuracy and stability compared to the PI controller, making it a superior choice for servo motor applications where nonlinearities and uncertainties are common. It is clear from the project that the servodrive with single-phase AC voltage as input converted to three-phase AC output using a variable frequency drive can be used in the motor for low power (less than 2 kW) robotic applications with low value of Total Harmonic Distortion (THD) ensuring smooth output, making it an ideal choice for small power and precision-driven applications.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The purpose of this chapter is to provide detailed explanation about the servo motor, its drive, motor design, about the project work covered, problem statement and its objective made which also covers about the organization made in the report.

1.1. SERVO MOTOR

Servomotors are considered as the heart of modern industrial applications and automation systems. They can be seen on hard drives, automatic doors, cruise control devices, robotic arms and many more. Although these motors are widely used, many controllers have been proposed and implemented to make them more efficient, they still suffer from nonlinearity, which affects overall efficiency. Fig. 1.1 shows a servomotor is used in robotic applications and changing loads, or any sudden change of the environment will make the whole system more complex. Servo motor systems have two outputs velocity and position that can be controlled. Disk drives and robotics are examples of applications where position control takes more importance than the speed control. Besides their shapes, they have to be designed effectively to get good magnetic linkage for all sort of applications i.e. lifting, cutting, and bracing.

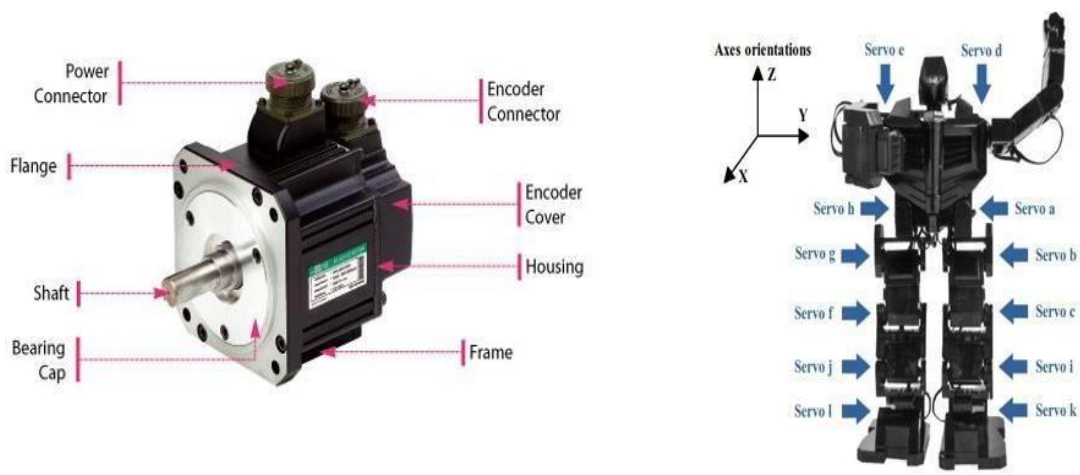


Fig. 1.1 Servomotor

In robotic welding applications, servo motors play the main role through which good precision and manageability for the manufacture of quality welds can be obtained. In the areas where the margin of error and precision are so tiny, servo motor is the best pick because it's able to provide the exact control over speed, torque, and accuracy. They can be a good example of intelligent machines that are able to make use of their intrinsic features that include fast motion control, high velocity, and precise welding. Braking systems merged with servo motors are a feature that allows them to stop even under the most difficult welding conditions and this is shown in Fig. 1.2. Besides, automation of the welding process via servo motors no only reduces chances for production of defective welding, but also speeds up production and efficiency of industries.

Fig. 1.2 Welding Robot

1.2. MARKET SURVEY OF SERVO MOTOR

Before designing a new product, it's crucial to conduct a market survey. The Global Servo Motor Market, valued at approximately USD 13.77 billion in 2024, is projected to expand to about USD 18.26 billion by 2029, indicating a compound annual growth rate (CAGR) of 5.82% during the forecast period (2024-2029) shown in Fig 1.3. This growth is due to the recent technological advancements and government policies, such as Minimum Energy Performance Standards (MEPS) implemented in various countries. These initiatives have encouraged the adoption of energy-efficient motor systems, consequently driving the demand for servo motors and drives.

The primary factor driving the market is the use of servo motors for automation. The developments in servo system technologies have captured the attention of end-users. These electrically powered devices find applications across diverse industries such as automotive manufacturing, packaging machinery, food processing, semiconductor manufacturing, and healthcare. In North America, the United States stands as the largest user of industrial robots in the Americas, representing approximately 79% of total installations in the region.

In the upcoming years, the servo motor market is expected to be highly competitive, with companies increasingly concentrating on developing new products to address any existing limitations. They are also looking into partnerships, mergers, and acquisitions to expand their customer base. The industries include ABB Ltd., Allied Motion Technologies, Inc., Ametek, Inc., General Electric Company, Nidec Corporation, Rockwell Automation Inc., Schneider Electric, Emerson Electric Company, Siemens AG, WEG Industries, Hitachi Ltd., Oriental Motor, Mitsubishi Electric Corp., and Yaskawa Electric Corp. are the key players in manufacturing servomotors globally.

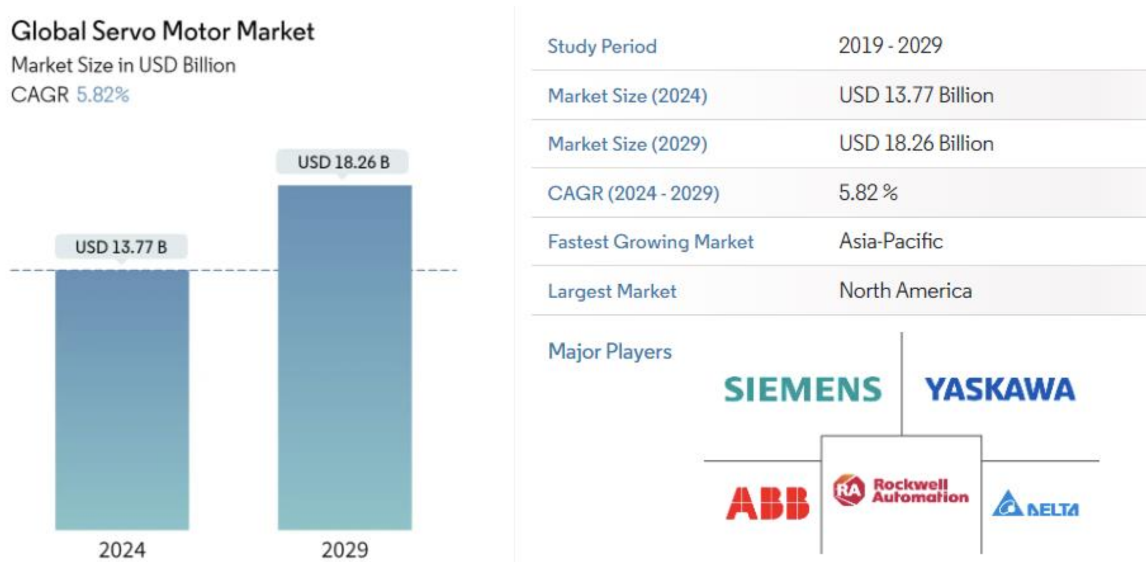


Fig. 1.3 Servomotor Market Analysis

Servo motors and drives are crucial parts of motion control systems, which regulate the position, speed, and acceleration of machines. A servo drive is an electronic device that provides power and control signals to the servo motor. Together, these components ensure precise and reliable control in various industries needing accurate operations. The servo motors and drives industry produces and supplies parts for motion control systems used in industrial automation, robotics, aerospace, and medical devices, among others.

1.3. TYPES OF SERVO MOTOR

1.3.1. ON THE BASIS OF ROTATION

1. **Positional Rotation Servos**: Positional servos have the capability to rotate the shaft approximately halfway around a circle and are equipped with safeguards to prevent the rotational sensor from over-rotation. These servos find extensive application in various contexts, including limb mechanisms, robotic arms, and other pertinent areas where precise positional control is paramount.
2. **Continuous Rotation Servos:** Continuous servos share a construction similar to positional servos, yet they possess the ability to move in both clockwise and anticlockwise directions. These servos are commonly employed in applications such as radar systems and robotics.
3. **Linear Servos:** Linear servos bear resemblance to positional servos but incorporate additional gears to convert circular motion into linear back-and-forth movement. These servos are commonly utilized in high-end model airplanes.

1.3.2. ON THE BASIS OF OPERATING SIGNAL

1. **Analog Servo motors:** Analog servos function through Pulse Width Modulation (PWM) signals, operating within a voltage range typically between 4.8 V and 6 V. In this servo type, PWM is inactive when the servo is at rest. The torque generated during idle periods can render the startup time ineffective.
2. **Digital Servo motors:** Digital servos utilize small microprocessors to receive signals and respond with high-frequency voltage pulses. This high pulse rate enables digital servos to deliver smooth and consistent torque responses. The digital servos typically consume more power compared to analog servos.

1.3.3. ON THE BASIS OF OPERATING POWER

1. **DC Servo Motor:** DC servos, also referred to as permanent magnet DC motors or separately excited DC motors, are employed for delivering rapid torque response. This reason behind the fast torque response is because of torque and flux are decoupled. DC servos stand out as one of the most widely utilized types of servo motors across various applications.

2. **AC Servo Motor:** AC servo motors are categorized into two types: 2-phase and 3-phase. The 2-phase squirrel cage servo motor is predominantly employed in low-power applications, while the 3-phase squirrel cage servo motor is preferred for high-power systems.

1.4. CONSTRUCTION OF SERVOMOTOR

STATOR

The stator of a servo motor is made of layered steel laminations that carry the windings. These windings are installed in slots cut axially along the inner perimeter of the stator. These windings can be arranged in either a star or a delta pattern. Each winding, is made up of several interconnected coils, one or more of which is inserted into each slot. The Fig. 1.4 shows the stator winding of a servomotor. Each of these windings is distributed around the stator's perimeter to produce an even number of poles. Depending on the power supply capabilities, the stator must be selected with the appropriate voltage rating.

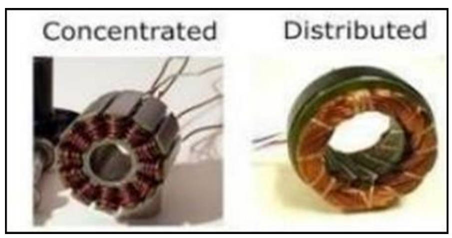


Fig. 1.4 Stator of Servomotor

ROTOR

The motor is constructed with various rotor configurations such as Inner Permanent Magnet (IPM) and Surface Permanent Motor (SPM). The permanent magnet is embedded at the outer surface of the rotor stator windings are kept stationary inside. The Fig. 1.5 shows the rotor with interior permanent magnet and the rotor with surface permanent magnet rotor is shown in Fig. 1.6.

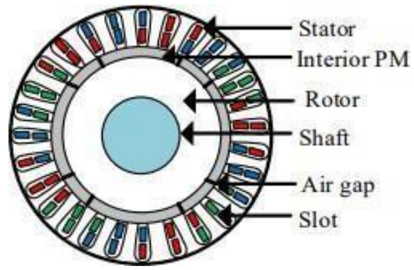


Fig. 1.5 Rotor with Interior PM

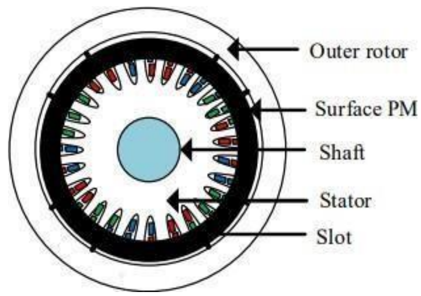


Fig. 1.6 Rotor with Surface PM

Table 1.1 Comparison of the Interior PM and Surface PM Features

Servo Motor Physical Design	Interior PM	Surface PM
Stator	Inner less core stator winding outside	Iron cored stator winding inside
Speed	High-speed motors are available.	Low and medium speed motor available
Inertia	Low inertia	High inertia
Noise	Quickly changing direction makes noisy	Noise less
Maintenance	Less maintenance	High Maintenance
Efficiency	High Efficiency	Less efficiency compares to the inner rotor
Torque	Minimum Torque	Produces more Torque
Power to weight ratio	Compare to outer run less	High
Gear box	Gear box required	No gear box required
Advantage	1. Rotating shaft moment of inertia is small 2. Compact Size	1. Increasing the torque capability and current. 2. Reducing heat dissipation

The Table 1.1 represents the comparison made for the interior PM and surface PM it proves that the inner rotor provides high efficiency and less torque.

Depending on the construction of the PM rotor, rotors in servo motor usually consist of permanent magnets and a shaft. Table 1.2 describes the comparison made forpermanent magnets in motors which can be classified into various types such as

1. Surface mounted magnet
2. Inserted magnet
3. Embedded type rotor magnets

Table 1.2. Comparison of the Various PM Rotor Structure

Content	Surface Magnet	Inserted Magnet	Buried Magnet
			
Torque	Very Good	Very Good	Very Good
Power factor	Power factor obtained is less	Power factor obtained is less	Power factor obtained is good
Efficiency	Less compared to buried	Less compared to buried type	Very high compared to other types

1.5. WORKING PRINICIPLE OF SERVO MOTOR

The working principle of the AC servo motor involves providing a steady AC voltage to the main winding of the motor's stator. Additionally, another stator terminal is connected directly to the control transformer via the control winding shown in Fig. 1.7.

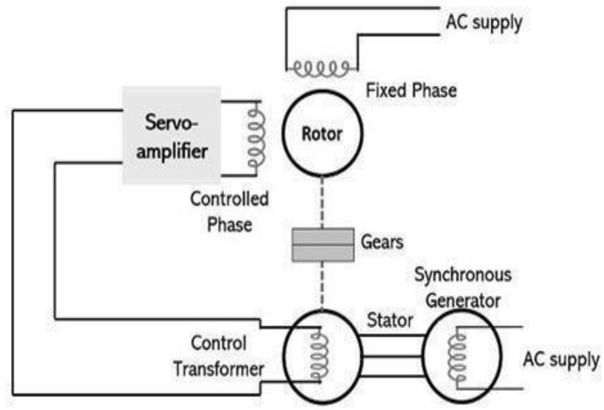


Fig. 1.7 Control circuit of Servomotor

In addition the control transformer's shaft is positioned at a specific angle, which is then compared to the angular position of the synchro generator's shaft. This comparison yields an error signal reflecting any discrepancies between the two angular positions. As a result of the reference voltage applied, the synchro generator's shaft rotates at a predetermined speed, assuming a particular angular orientation.

Specifically, the voltage levels corresponding to equivalent shaft positions are assessed to generate the error signal. Subsequently, this error signal interacts with the current voltage level at the control transformer. It is then transmitted to the servo amplifier, which generates a corrective control voltage. This applied voltage enables the rotor to attain a specific speed, initiating rotation and sustaining it until the error signal diminishes to zero, thereby achieving the desired motor position within the AC servo motor system.

1.6. CHARACTERISTICS OF SERVO MOTOR

The Torque-Speed characteristics of an AC servo motor shown in Fig. 1.8. In the following characteristics the torque varies with speed, but not linearly. This behavior is primarily determined by the ratio of reactance (X) to resistance (R). A lower ratio signifies higher resistance and lower reactance in the motor. Consequently, motors with lower X-R ratios tend to exhibit more linear characteristics compared to those with higher X-R ratios.

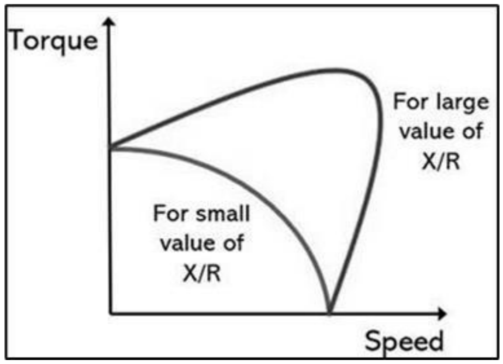


Fig. 1.8 Torque-Speed Characteristics

1.7. SPEED CONTROL METHODS

Position Control: This method is employed to determine the rotational speed based on external input frequency signals. The angle of revolution is determined by the number of pulses. Both the position and velocity of a servo motor can be precisely controlled via communication.

Torque Control: This method involves setting the output torque of the servo motor via analog input at a specified address. Torque adjustments can be made in real-time by simply modifying the analog input. Furthermore, communication allows for the alteration of values at relative addresses.

Speed Control: In this approach, motor speed regulation can be achieved through analog input and pulses. When precision is predominant and high torque is not a primary concern, the speed control is more effective. The control algorithm of the servomotor is shown in Fig. 1.9.

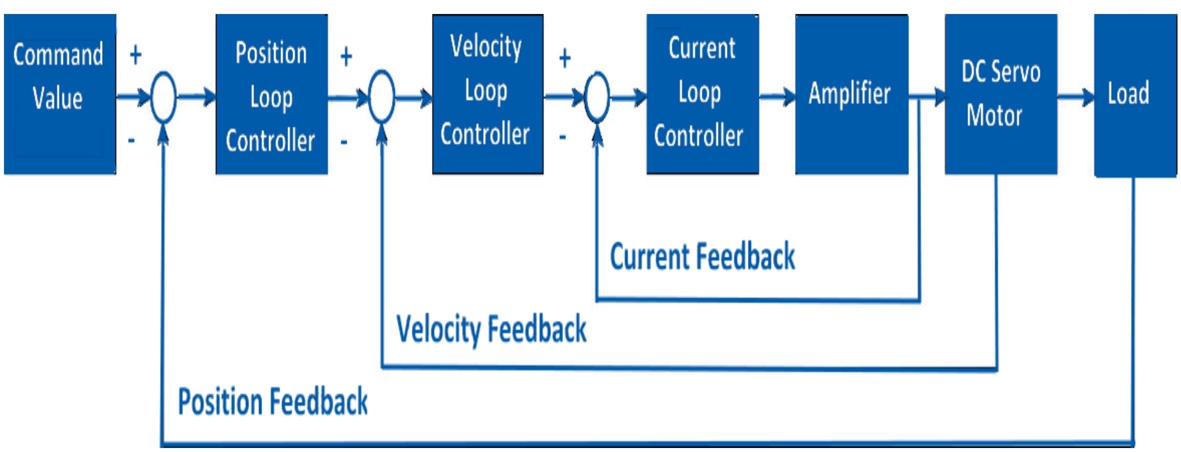


Fig. 1.9 Control Algorithm of Servomotor

1.8. ADVANTAGES OF SERVOMOTOR

- The speed control characteristics of this motor are good.
- They generate less amount of heat.
- They offer high efficiency, more torque per weight, reliability & reduced RF noise.
- They need less maintenance.
- They have a longer life expectancy in the non-existence of a commutator.
- These motors are capable of handling higher current surges in industrial machinery.
- At high speeds, they offer more constant torque.
- These are highly reliable.
- They provide high-speed performance.
- These are well-suitable to unstable load applications.

1.9. DISADVANTAGES OF SERVOMOTOR

- AC servo motor control is more difficult.
- These motors can be broken by constant overload.
- Gearboxes are frequently necessary to transmit power at high speeds.

1.10. SINGLE PHASE INPUT TO THREE PHASE OUTPUT

Single-phase input to three-phase output converters are often used in low power applications for several reasons:

Cost-effectiveness: Single-phase power supply normally are cheaper than three-phase power supply. The application of single-phase input by itself minimizes the cost in unit and supply infrastructure.

Simplicity: Transforming the single-phase input to the three-phase output can be easier and usually require less complex circuitry This makes for lower manufacturing cost as they have fewer components.

Compatibility: A lot of low-power applications are meant to be driven by single-phase AC power systems that are typical of the small motors, pumps, fans, etc. These devices can function using a single-phase to three-phase converter and does not require modifications to current infrastructure making it connect to standard single-phase outlets.

Overall, the use of single-phase input to three-phase output converters offers a cost-effective solution for low-power applications less than 10 kW.

1.11. PROBLEM STATEMENT

In India, for low power industrial applications there is no indigeneous servodrive with single-phase input converted to three phase output. And also significant challenge in implementing a proportional-integral (PI) controller for field-oriented control (FOC) in motor drives is tuning the controller parameters to achieve desired performance characteristics such as fast response and stability across varying operating conditions. This involves finding optimal values for the proportional (Kp) and integral (Ki) gains, ensuring satisfactory performance across the entire operating range while maintaining stability among varying dynamics, load torque, speed, and voltage fluctuations.

1.12. OBJECTIVE OF THE PROJECT

- The overall objective of this project is to design a servodrive with single-phase input (230 V AC, 50 Hz) converted to three-phase output (200 V AC, 375 Hz) using a variable frequency drive.
- The development of this schematic involves consideration of factors such as voltage and current ratings, switching frequencies, and power loss of the diode and IGBT module.
- Choosing the best control strategy for control of servomotor.
- Analyzing the servodrive using two distinct control methodologies: Proportional-Integral (PI) control and fuzzy logic control.

1.13. ORGANIZATION OF THE REPORT

There are eight chapters in this report. Below is a list of each chapter's contents.

Chapter 2 - Discusses the literature review.

Chapter 3 - Discusses the power schematic design of the servodrive.

Chapter 4 - Discusses the power module chosen and the power loss calculation.

Chapter 5 - Discusses the different motor control algorithms and PWM technique

Chapter 6 - Explains the proposed methodology used in this project and analysis of the drive using PI and Fuzzy Logic Controller.

Chapter 7 - Discusses the simulation and its results.

Chapter 8 - Discusses the conclusion and future work.

CHAPTER 2
LITERATURE REVIEW

The purpose of this chapter is to provide literature review about the construction of Servomotor, different control algorithm for servomotor, and its PWM control strategies. A detailed discussion about controller algorithm and the PWM modulation techniques are given.

H. M. Flieh, R. D. Lorenz, E. Totoki, S. Yamaguchi and Y. Nakamura, "Investigation of Different Servo Motor Designs for Servo Cycle Operations and Loss Minimizing Control Performance," IEEE Transactions on Industry Applications, vol. 54, no. 6, pp. 5791-5801, Nov.-Dec. 2018 [1]

Servo motors are widely used in many industrial applications. These motors require precise control of acceleration, speed, and position. Different designs can be found in the literature. This paper will compare the response of two common types and will propose a new servo motor design that uses less magnet, lowering the price of the motor. The proposed motor would be able to save energy for the required application (minimize cost industrial process cost) and would be suitable for high-frequency injection based self-sensing techniques.

Y. Yasa, E. Sahin, C. Acar, A. Gozutok, E. Firat and E. Mese, "Servo motor driver design for high performance applications," 3rd International Conference on Electric Power and Energy Conversion Systems, Istanbul, Turkey, 2013 [2]

The motion control applications have become quite common in recent years. This makes the design and control of the motor very popular. Especially in high performance applications, permanent magnet synchronous motors, which are often called servo motor, are used nowadays. The driver is supplied by battery as DC source and its energy management is important as an enabler of longer battery life. A solution is presented for a reasonable battery energy management. Simulations are performed at both circuit and system levels before the experimental prototype have been built. Validation of the driver prototype has been performed with a PMSM motor and the results are quite promising before transition starts into the production stage.

S. Lee, C. Hwang, J. Shim and J. Ha, "A Control Method of Servo Motor Drives for Fast Dynamic Response and Low Torque Ripple," IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022, pp. 01-05, doi: 10.1109/ECCE50734.2022.9947638 [3]

This paper proposes a hybrid control method of servo motor drives for fast dynamic response and low torque ripple. A duty modulated direct torque control (DMDTC) with a variable control period is proposed to achieve a fast dynamic response at a transient-state. Low torque ripple is achieved through the conventional field-oriented control (FOC) at a steady-state. In addition, a smooth transition method from the DMDTC to FOC is introduced. Experimental results verify the proposed control method with a surface-mounted permanent magnet synchronous motor (SMPMSM).

H. J. van de Straete, P. Degezelle, J. De Schutter and R. J. M. Belmans, "Servo motor selection criterion for mechatronic applications," IEEE/ASME Transactions on Mechatronics, vol. 3, no. 1, pp. 43-50, March 1998 [4]

Modern mechatronic applications often involve complex motions, resulting in highly dynamic motor loads. The selection of an appropriate motor is based on the characteristics of the load, besides other technical, as well as economic, considerations. However, motor characteristics, such as rotor inertia, affect the motor load, which complicates the analysis. The selection criterion presented in this paper separates the motor characteristics from the load characteristics and its graphical representation facilitates the feasibility check of a certain drive and the comparison between different systems. In addition, it yields the range of possible transmission ratios. The method is illustrated with an industrial case study.

M. Md Kamal and N. Mamat, "Controller design for Servo Motor," IEEE Symposium on Industrial Electronics & Applications, Kuala Lumpur, Malaysia, 2009, pp. 926-929 [5]

The objective of this paper is to design a controller for Servo Motor in discrete-time systems. The effect of sampling time on the proposed design will further discussed. Real-time data gained from the experimental is used to obtain the transfer function to design the PID controller. In order to get the optimal value of PID controller, ARX model structure was implemented. The effectiveness of the design is validated using MATLAB/Simulink. From the results obtained, it shows that the output for PID controller will gives the best performance of 87.79% at 55 ms sampling time.

A. K. Chakraborty and N. Sharma, "Control of permanent magnet synchronous motor (PMSM) using vector control approach," IEEE/PES Transmission and Distribution Conference and Exposition (T&D), Dallas, TX, USA, 2016 [6]

Permanent magnet synchronous motors (PMSM) are mainly used in high-performance and high-efficiency motor drives such as used in railways. PMSM has the performance required for traction motors and is more compact, light weighted and efficient than induction motors. This paper presents the detailed modeling of PMSM drive in Simulink environment and also presents the speed control of PMSM using vector control approach and by use of state feedback (SFB) controller. The observer is designed to eliminate the need of sensors. The observer is designed for estimating any one of the state variable if the other state variable is known thus eliminating the need to sense both speed and current. The state feedback (SFB) controller is designed such to provide zero steady state error.

Gupta, B. Singh, and C. Choudhury, "Comparative Analysis of Fuzzy Logic and PI Controller for Field-Oriented Control of PMSM," IEEE Transactions on Industrial Electronics, vol. 65, no. 8, pp. 6543-6552, 2018 [7]

This paper makes a comparative study between the fuzzy logic control and the proportional-integral (PI) control methods when DC link voltage is controlled in Saw tooth wave transition in Permanent Magnet Synchronous motors (PMSM). The research values two control strategies and examines their role in achieving motor precision torque and flux control that are the core of PMSM operation. During this part, the topic on the comparative metric (e.g. rate of acceleration, torque response, efficiency, etc.) or the ability to stay fast on fluctuating parameters or external disturbances will be also addressed. The paper delivers contribution to a comprehension regarding the case of usage of fuzzy logic and PI controllers in PMSM which are PMSM systems with the help of an inconsistency analysis and makes it possible to estimate appropriate control strategies based on application requirements and system specifications.

B. Sonkriwal, P.R.D. and H. Tiwari, “Analysis of Sliding mode, Fuzzy PI and PI Control Strategies for Permanent Magnetic Synchronous Motor Drive,” IEEE 3rd International Conference on Sustainable Energy and Future Electric Transportation (SEFET), Bhubaneswar, India, 2023 [8]

Permanent magnetic synchronous motor (PMSM) drive is one of the industry's most well-known AC motor drives. This motor is used in a variety of platforms due to its advantages over other AC drives, which include its compact size, light weight, broad speed range, high power factor, high efficiency, and high overload capacity. Based on the field orientation control (vector control), a technique for controlling PMSM drives utilizing space vector pulse width modulation (SVPWM) is employed. As the PMSM-drive possesses non-linearity, strong coupling, and time-varying parameters, it is not self-tuning for the PI controller with the variable system states. Furthermore, the PI controller has a large overshoot, steady-state error, torque ripples, and a slow response with variable states.

A. Dumitrescu, D. Fodor, T. Jokinen, M. Rosu and S. Bucurenciu, "Modeling and simulation of electric drive systems using MATLAB/Simulink environments," IEEE International ElectricMachines and Drives Conference, Seattle, WA,USA, 1999 [9]

This paper describes a complete modeling and simulation realization on a closed loop induction servomotor drive based on the MATLAB/Simulink environment. A simple modeling approach for different types of inverters, based on the dynamic node technique is proposed and a servomotor drive library is described. Based on this library, a speed sensor and/or speed sensorless vector control strategy is implemented.

M. F. Shams, M. S. Alam, and M. A. Rahman, "Performance comparison of PI and fuzzy controllers for speed control of PMSM," IEEE International Conference on Industrial Technology, vol. 4, pp. 1707-1712, 2019 [10]

This work deals with the comparative analysis of PI and fuzzy type controllers for PMSM (Permanent Magnet Synchronous Motor) speed control. The goal of this research is to determine whether these control methods to bring the revolution of PMSMs speed which is a vital factor for their applications in various industrial fields. The content is likely to describe the design, implementation, as well as performance evaluation of both the classic as well as the fuzzy controllers, discussing the aspects of control algorithm development, simulation and experimental results. The most probably discussed performance evaluation metrics are reliability, stability, speed accuracy, responsiveness to disturbances and parameter variations. Summing up, the essay compares the PI and fuzzy control strategies for PMSM speed regulation and contributes to the understanding of their pros and cons to enable the selection of suitable control solution depending on application-specific requirements and system characteristics.

R. Rao, K. K. Jha, and S. K. Panda, "Comparative Study of PI, Fuzzy, and Neuro-Fuzzy Controllers for Field Oriented Control of PMSM," IEEE Transactions on Power Electronics, vol. 30, no. 3, pp. 1512-1523, 2015 [11]

The paper focuses on a comparative analysis of three control methodologies such as PI, fuzzy logic and neuro-fuzzy control are applied to FOC of PMSM. Parameters such as how quickly does the system respond to torque, how well does the system regulate speed, how efficient is the system and how resilient it is to parameter variation and or disturbances listed are a few of the metrics likely discussed to give a holistic comparison. The comparison of the PIs fuzzy logic, and neuro fuzzy controllers for the FOC is an intelligent idea, through which this paper tries to add something to the existing of knowledge about the strengths and weaknesses of these techniques for use in FOC of PMSMs for helping in the future leaders and the designers in the selection of the most appropriate technique based on the need of the application and the system constraints.

S. Jain and N. Verma, "Comparison of Fuzzy Logic Controller and PI Controller for Speed Control of PMSM," IEEE Transactions on Industrial Informatics, vol. 14, no. 5, pp. 2267-2276, 2018 [12]

The paper makes a comparison of two control methods based on fuzzy logic and PI control for the speed rapport of Permanent Magnet Synchronous Motor (PMSM). Performance comparison metrics like tracking speed accuracy, system stability, and resistance to disturbances or model parameter variations will totally be part of their discussion to get an all-round comparison between the two control techniques. By this comparative research, the paper is intended to contribute to the knowledge of suitability and effectiveness of fuzzy logic and PI controllers in speed control of PMSM. The results can be helpful for engineering and science professionals in selection of the best control strategy in accordance with what is more appropriate to specific applications and system peculiarities.

S. J. Patil and R. S. Patil, "Performance Comparison of PI and Fuzzy Controllers for Speed Control of PMSM Drive," IEEE Transactions on Power Systems, vol. 34, no. 2, pp. 1183-1194, 2019 [13]

A comparison between proportional-integral (PI) and fuzzy algorithms for the speed control of Permanent Magnet Synchronous Motor (PMSM) drives. Aspects mentioned are control algorithm development, simulation studies and experimental validation. Metrics like time tracking accuracy, response time, stability and robustness to disturbances and parameter variations are probabilities assessed to offer a complete overview of the two control strategies mentioned. The paper will make it possible to perform a comparative analysis of both PI and fuzzy controllers for PMSM drives and to contribute to the military with the effectiveness and appropriateness of the controllers, which could help choosing the right controller by engineers and researchers based on specific application and system constraints.

S. R. Mishra and S. K. Gupta, "Comparison of PI and Fuzzy Logic Controllers for Speed Control of PMSM," IEEE Transactions on Control Systems Technology, vol. 28, no. 6, pp. 2397- 2020 [14]

A comparative analysis between PI and Fuzzy logic controllers for the control of speed of electric PMSMs. The goal of the study is to measure the level of achieving precise speed control that is crucial to the efficient operation of PMSMs in various control systems applications thus putting into consideration the control techniques. The subject is about the construction of PI and fuzzy logic controllers, covering the topic of control algorithm creation, simulation studies, and experimenting. The goal here is the use of denotation process to compare PI and fuzzy logic as speed regulation in PMSMs control and to contribute insights into the effectiveness and suitability of both control strategies for varied application requirements as well as system constraints.

V. S. Choudhari and A. M. Kuthe, "Comparative Analysis of PI and Fuzzy Logic Controllers for Speed Control of PMSM," IEEE Transactions on Industrial Applications, vol. 50, no. 4, pp. 2257-2266, 2019 [15]

This study aims at developing speed regulation techniques for Permanent Magnet Synchronous Motor (PMSM). PMSMs are widely employed in AC servo motors because of their several advantages namely, high torque-to-weight ratio, power density, efficiency and power factor. Although conventional Proportional-Integral (PI) controller improves PMSM parameters, it may incur in low performance whenever the dynamics of system changes across time or with operating conditions. As a solution to this matter, this paper suggests the use of Fuzzy Logic Controller (FLC) instead of PI controller. Comparison of the speed responses of the two controllers MATLAB/Simulink under different operating conditions, verifying the domination of the FLC controlled PMSM over the PID controlled PMSM.

CHAPTER 3

POWER SCHEMATIC DESIGN

This chapter analyzes the power schematic of the drive and study of Total Harmonic Distortion (THD) in existing drives. Also, the Input Current THD and Order of Harmonics of the power schematic.

3.1. HARMONIC REDUCTION METHODS IN AC DRIVES

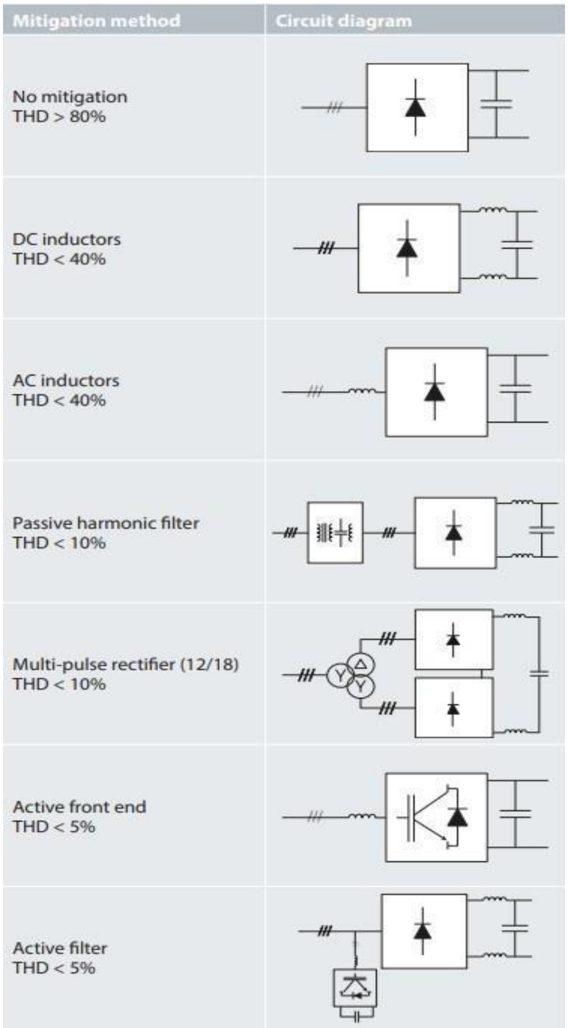


Fig. 3.1 Harmonic Reduction Methods in AC drives

Fig. 3.1 represents the harmonic reduction methods in AC drives using passive filter and Active Filters. From the figure, it can be inferred that by using DC inductors, the Total Harmonic Distortion (THD) can be reduced to less than 40%.

3.2. POWER QUALITY ANALYSIS OF EXISTING DRIVES

Table 3.1 Specifications of DANFOSS DRIVE (FC - 301)

Sl. No.	Parameters	RATINGS
1.	Power	5.5 kW (400 V)/ 7.5 HP (460 V)
2.	Input Voltage, Frequency and Current	3x380-480 V, 50/60 Hz, 11.7/9.9 A
3.	Output Voltage, Frequency and Current	3x0-Vin, 0-1000 Hz, 13/11A

Table 3.2 Specifications of FANUC DRIVE (A06B-6116-H011#H560)

Sl. No.	Parameters	RATINGS
1.	Power	13.2 kW (283 – 339 V)
2.	Maximum Input Voltage, Frequency and Current	3 x 200-240 V, 50/60 Hz, 39 A at 200 V
3.	Maximum Output Voltage and Current	240 V, 48 A

The specifications of DANFOSS drive (FC – 301) and FANUC drive (A06B-6116-H011#H560) is listed above in Table 3.1 and Table 3.2.

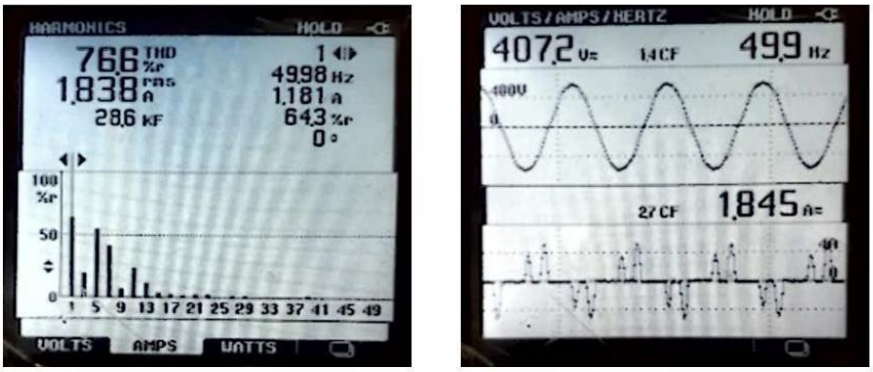


Fig. 3.2 Current and Voltage THD of DANFOSS Drive

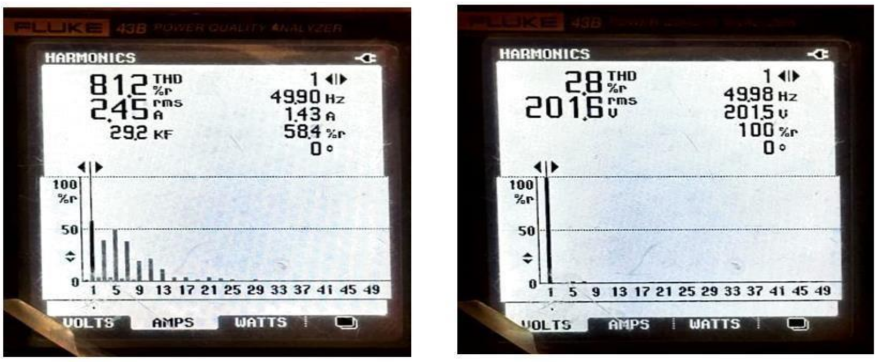


Fig. 3.3 Current and Voltage THD of FANUC Drive

By measuring the Total Harmonic Distortion (THD) of current and voltage in drives like Danfoss and FANUC using a Fluke power quality analyzer helps understand how much the electrical signals deviate from their pure sinusoidal waveform. Fig. 3.2 and Fig. 3.3 represents the current and voltage THD of Danfoss and Fanuc Drive. The Fig. 3.4 shows the test bench setup of power quality analysis of FANUC drive.

Fig. 3.4 Test Bench Setup for Power Quality Analysis

3.3. POWER SCHEMATIC WITH DC LINK CAPACITOR ONLY

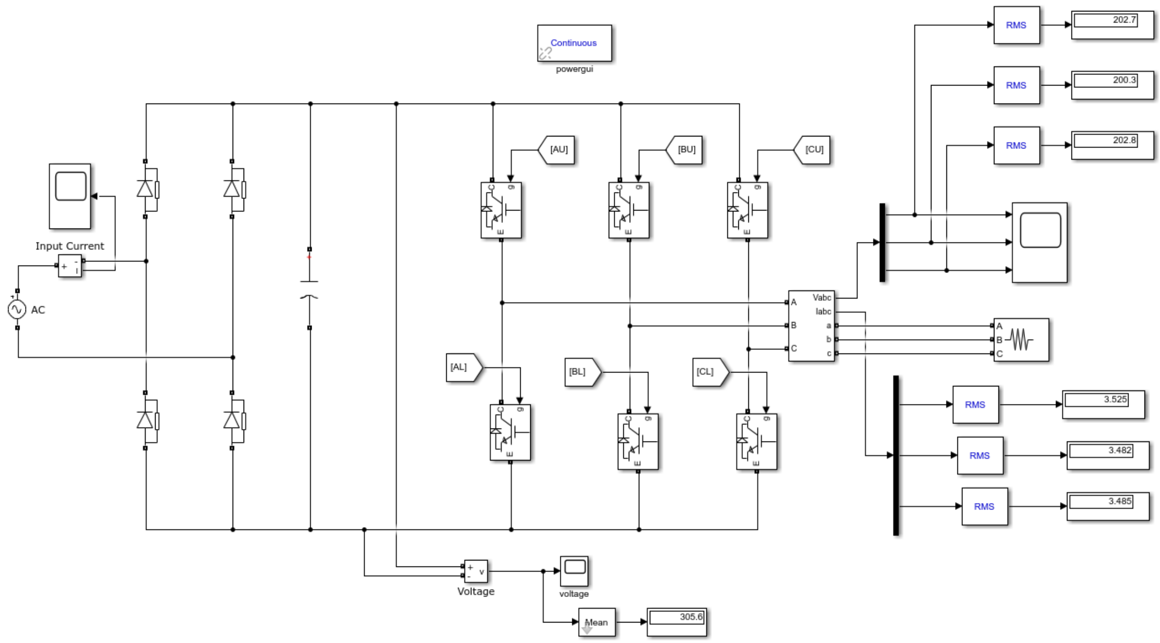


Fig. 3.5 Power Schematic with DC link Capacitor only

A power schematic with a DC link capacitor consists of a DC source connected to a converter or inverter, with a capacitor stabilizing the DC voltage by mitigating ripple effects and providing energy storage. The Fig. 3.5 represents the power schematic with DC link capacitor simulated in MATLAB/Simulink.

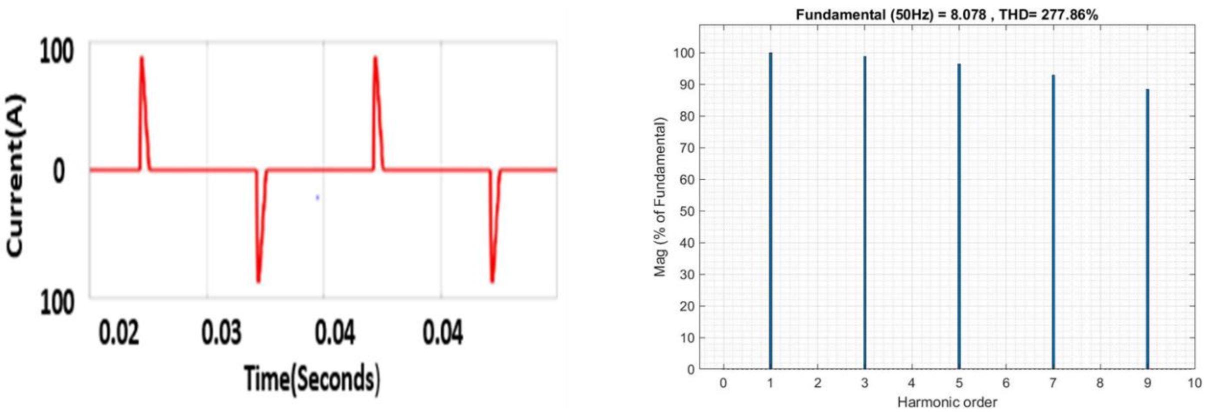


Fig. 3.6 Input current waveform and Harmonics order

By recognizing the order of the harmonic present in input current waveform is another issue to be taken into consideration because it can be used to identify the specific frequency components that are causing the distortion and the necessary correcting measures can be taken to optimize the systems operation and ensure that it complies with all the regulatory standards. The Fig. 3.6 represents the Input Current THD and the order of Harmonics.

3.4. POWER SCHEMATIC WITH +VE RAIL INDUCTOR

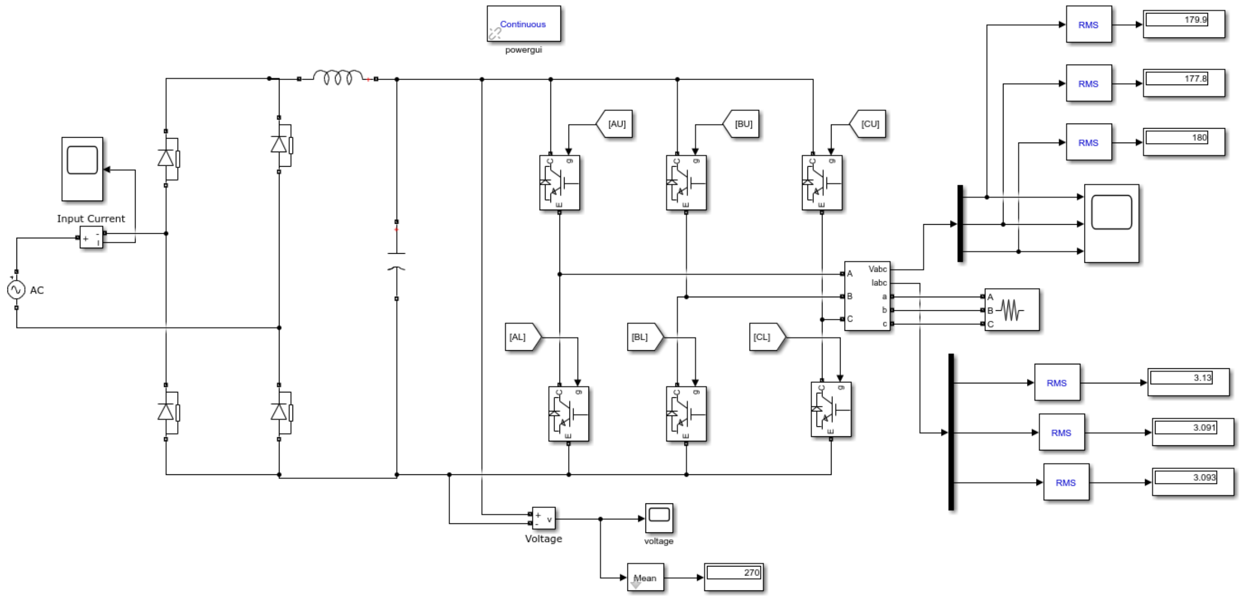


Fig. 3.7 Power Schematic with +ve Rail Inductor

The Fig. 3.7 represents the power schematic of drive with DC link capacitor and +ve rail inductor simulated in MATLAB/Simulink.

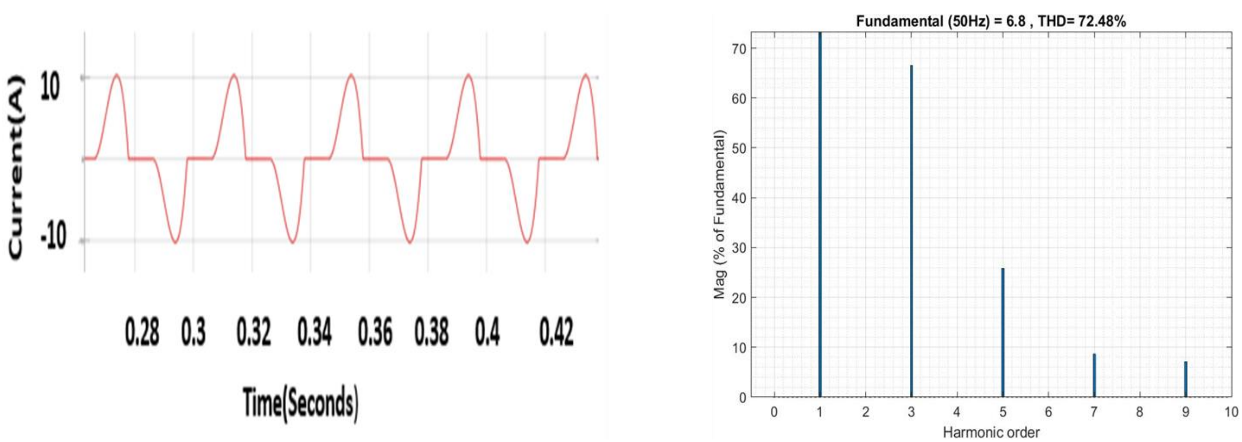


Fig. 3.8 Input Current Waveform and Order of Harmonics

The Figure 3.8 illustrate the input current Total Harmonic Distortion (THD) and the order of the harmonics respectively.

3.5. POWER SCHEMATIC WITH +VE and –VE RAIL INDUCTORS

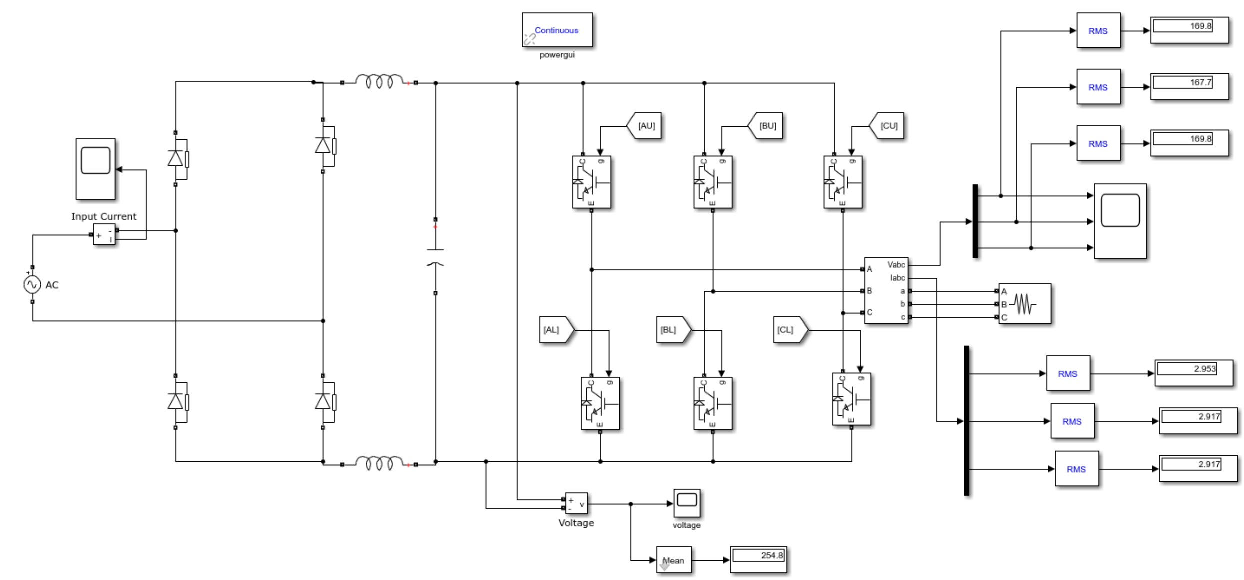


Fig. 3.9 Power Schematic with both +ve and -ve Rail Inductor

The Fig. 3.9 represents the power schematic with both +ve and -ve DC rail inductors simulated in MATLAB/Simulink.

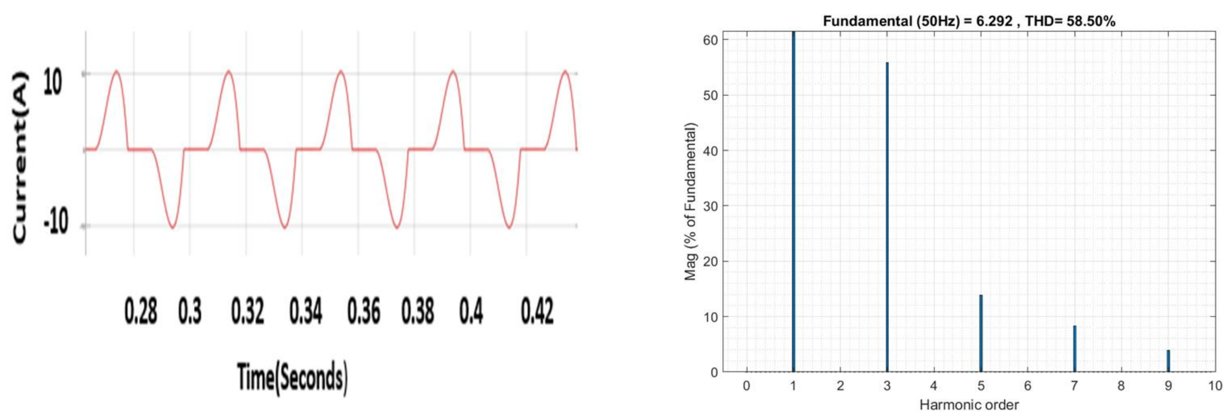


Fig. 3.10 Input Current waveform and Order of Harmonics

The significance of recognizing the order of harmonics and THD in the input current waveform is that it allows for the identification of the specific frequency components causing distortion. The Fig. 3.10 represents the Input Current THD waveform and Order of Harmonics of the power schematic with both +ve and -ve rail inductors.

3.6. COMPARISON BETWEEN DIFFERENT POWER SCHEMATIC

Table 3.3 Comparison of Three Power Schematic parameters

Power Schematic Topology	**DC Link Voltage**	**Source Current THD @ PCC**
DC Link Capacitor only	305.6 V	277.86%
DC Link Capacitor with +ve rail Inductor	270 V	72.48%
DC Link Capacitor with both +ve and -ve rail Inductors	254.8 V	58.5%

By comparing the three power schematic listed in the Table 3.3, the schematic with DC link capacitor with +ve rail inductor has a DC link voltage of 270 V and the source current THD at the point of common coupling of 72.88% which is preferred.

CHAPTER 4
POWER LOSS ANALYSIS

This chapter analyzes the switches used for the diode bridge rectifier and inverter. Also, the power loss of the switches at the rated loaded condition is calculated using DANFOSS SEMISEL software.

4.1. POWER SCHEMATIC OF SERVODRIVE

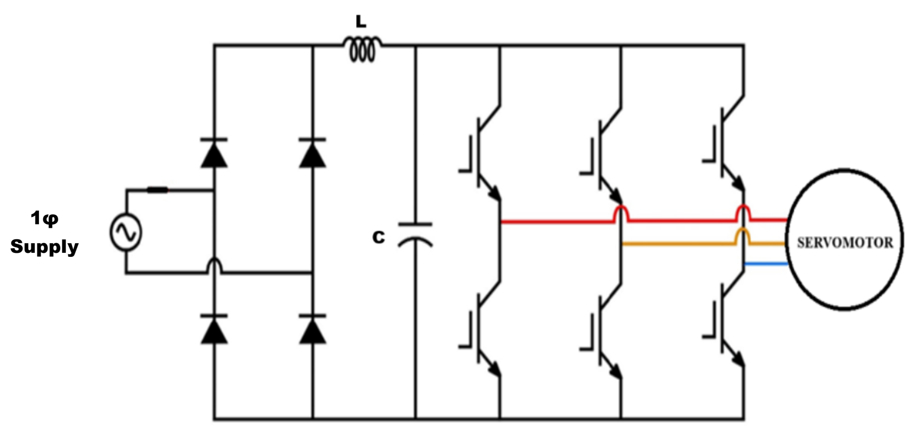


Fig. 4.1 Power Schematic of Servodrive

. By comparing the above three power schematic and the results, the power schematic with DC link capacitor with +ve rail Inductor which is shown in Fig. 4.1 and it is the most efficient one and the DC link voltage is within the limit.

4.2. DIODE BRIDGE RECTIFIER

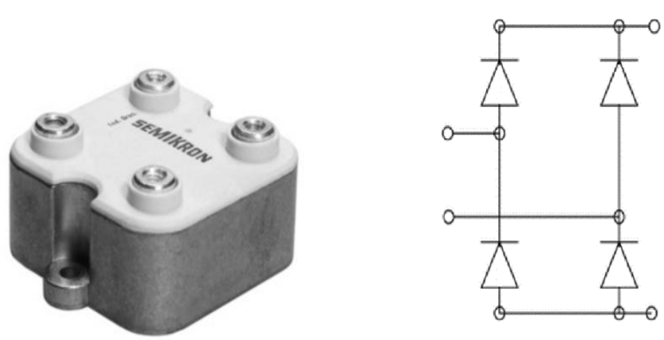


Fig. 4.2 Semikron SKB 30/16 A1

The power module chosen for the diode bridge rectifier is Semikron SKB 30/16 A1 is shown in Fig. 4.2.

4.2.1. SPECIFICATIONS OF SKB 30/16 A1 USED IN THIS PROJECT

Table 4.1 Electrical Characteristics of SKB 30/16 A1

Parameters	Values
Input Voltage (V_{RMS})	1600 V
Forward RMS Current (I_D)	15 A
Input Frequency	50/60 Hz
Forward Surge Current Maximum (I_{FSM})	370 A

The specifications of the diode bridge rectifier module SKB 30/16 A1 are shown in Table 4.1. The input voltage given to the module 230 V at a frequency of 50 Hz and the input RMS current of 3.83 A.

4.2.2. TEMPERATURE OF POWER MODULE

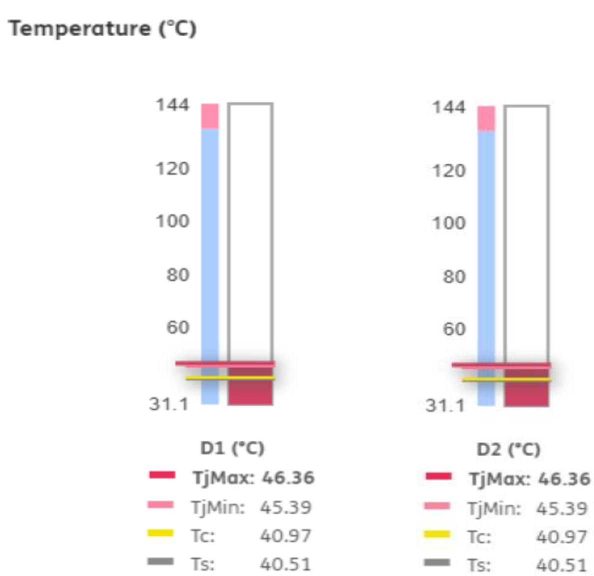


Fig. 4.3 Temperature of power module

The maximum junction temperature of 46.36 °C and minimum junction temperature of 45.39 °C in the module, case temperature of 40.97 °C and the heat sink temperature of 40.51 °C is shown in Fig. 4.3.

4.2.3. TRANSIENT THERMAL RESISTANCE

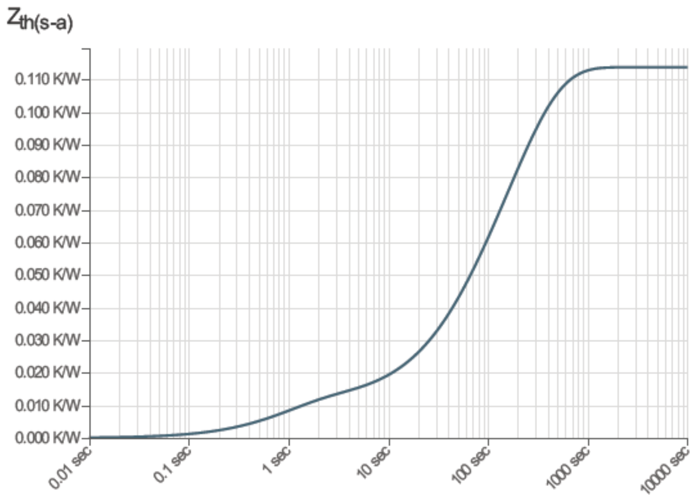


Fig. 4.4 Z_{th} Graph

Transient thermal resistance (Z_{th}) in a heat sink refers to the measure of how quickly the heat sink can dissipate heat from a component or device under transient (changing) thermal conditions which is shown in Fig. 4.4. It indicates how effectively the heat sink can respond to sudden changes in heat load or ambient temperature.

4.2.4. POWER LOSS OF MODULE

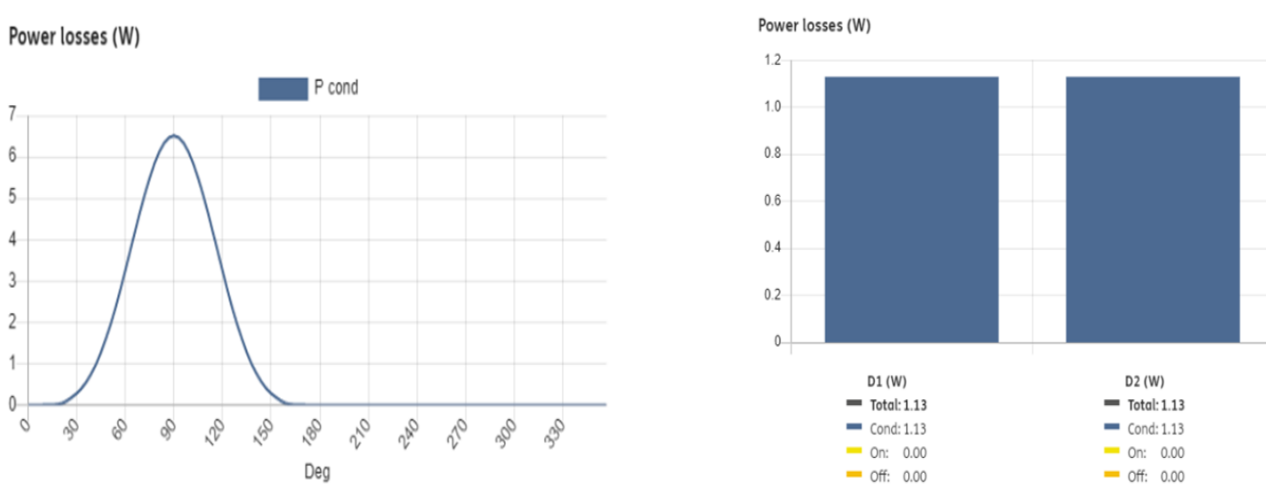


Fig. 4.5 Total power loss of module

The Fig. 4.5 shows the power loss of the module over the single output time period (0-360) degree and the maximum power loss of approximately 6.5 W at 90 degree and the total conduction loss of 1.13 W and the switching loss during on and off time is zero.

4.3. IGBT POWER MODULE

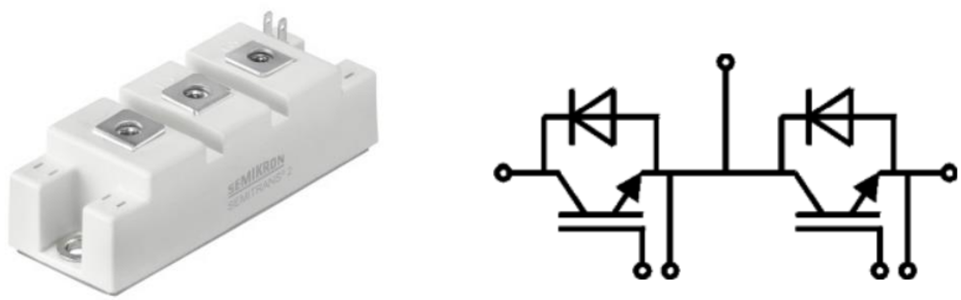


Fig. 4.6 Semikron SKM75GB12T4

The power module chosen for the three-phase inverter is Semikron SKM75GB12T4 is shown in Fig. 4.6. Three stacks of the module will be connected in a cascade network for the three-phase inverter.

4.3.1. SPECIFICATIONS OF SKM75GB12T4 USED IN THIS PROJECT

Table 4.2 Specifications of SKM75GB12T4

Parameters	Values
Collector Emitter Voltage (V_{CES})	1200 V
Collector Current (I_C)	115 A
Collector Surge Maximum Current (I_{CSM})	225 A
Gate-Emitter Voltage	-20 V to 20 V
Switching Frequency	1.6 MHz

The specifications of the IGBT power module SKM75GB12T4 are shown in Table 4.2. The input DC link voltage given to the module is 320 V and the output voltage of 200 V at a frequency of 375 Hz. The switching frequency of the output is 2 kHz. The modulation technique used is Space Vector Pulse Width Modulation (SVPWM).

4.3.2. TEMPERATURE OF POWER MODULE

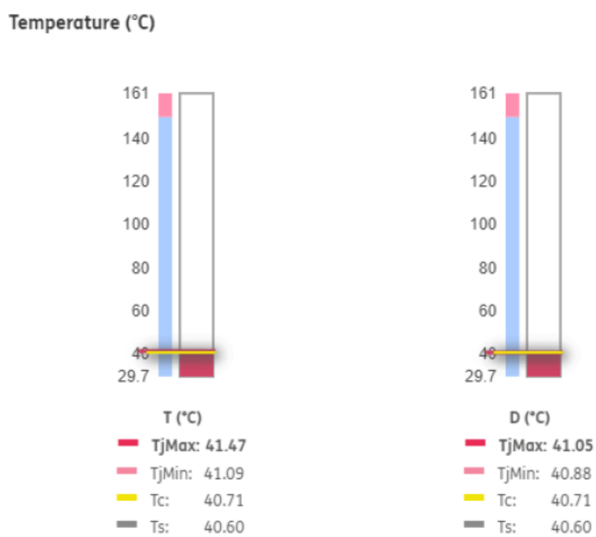


Fig. 4.7 Temperature of IGBT module

The maximum junction temperature of 41.47 °C and minimum junction temperature of 41.09 °C in the module, case temperature of 40.71 °C and the heat sink temperature of 40.60 °C is shown in Fig. 4.7.

4.3.3. POWER LOSS AND EFFICIENCY OF IGBT MODULE

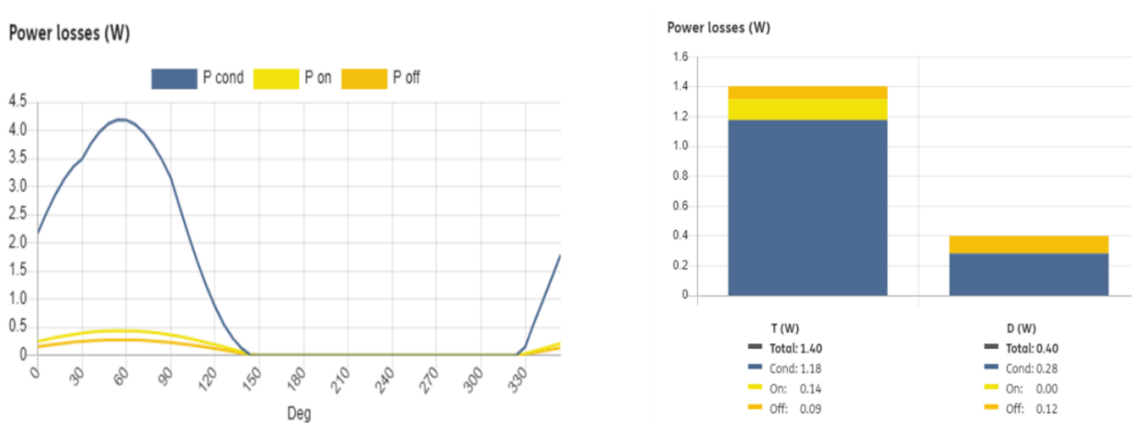


Fig. 4.8 Power Loss of IGBT module

Table 4.3 Efficiency of IGBT module

Parameters	Values
Efficiency	99.11 %
Circuit Losses	10.81 W

The Fig. 4.8 shows the power loss of the module over the one time period of the output (0-360) degree and the maximum power loss of approximately 4.2 W at 60 degree and the total loss of 1.40 W in which conduction loss is 1.18 W and the switching loss during the ON time period is 0.14 W and at the OFF time period is 0.09 W. The efficiency of the IGBT module is 99.11 % shown in Table 4.3.

CHAPTER 5

MOTOR CONTROL ALGORITHMS

This chapter explains the control algorithms used for different motors its system specification. Also, the modulation technique as the SVPWM technique considered for this project work.

5.1. MOTOR CONTROL ALGORITHMS

The field of motor control has undergone rapid expansion due mainly to the advantages of semiconductors in both power and signal electronics and the processing capability of microprocessors and DSPs. These technological improvements have enabled the development of really effective drive control with ever lower power dissipation hardware and evermore accurate control structures. The electrical drive controls have become more accurate in thesense that not only are the DC current and voltage controlled but also the three-phase currents and voltages are managed by the combined use of MCU and software algorithms.

5.1.1. TYPES OF MOTOR CONTROL ALGORITHM

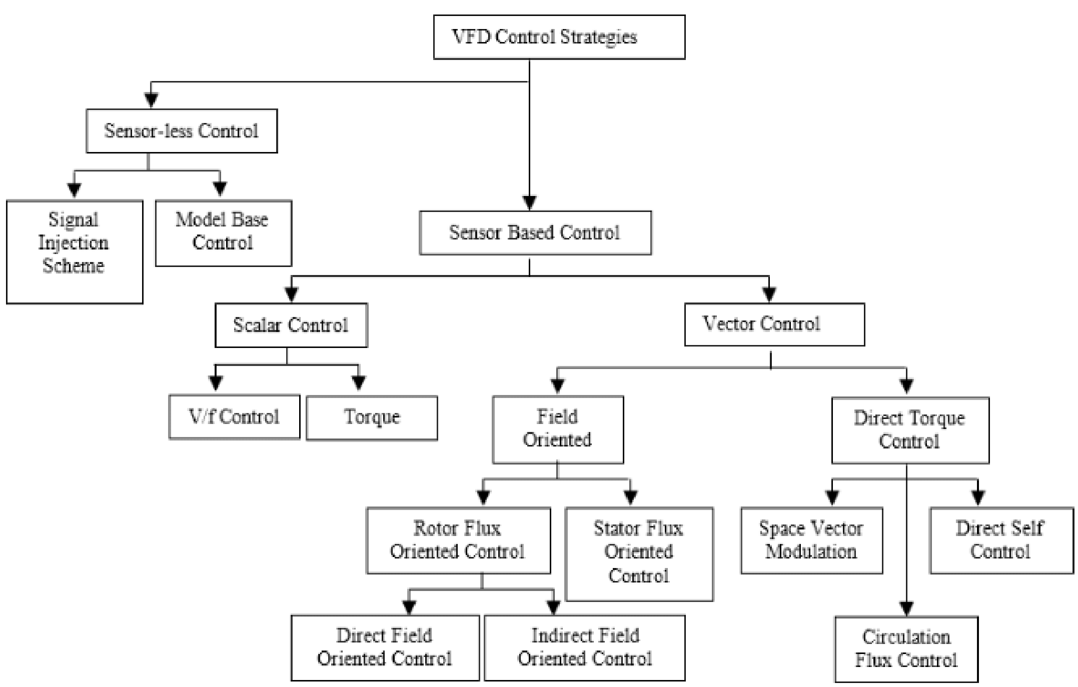


Fig. 5.1 Types of Motor Control Algorithm

The Figure 5.1. represents the types of motor control algorithm used in various motors. Based on the Table 5.1 the comparison table describes for which control algorithm, the motor type used, their torque controllability and the feedback sensor used.

Table 5.1 Motor Control Algorithm Comparison

Control Algorithm	Motor Type	Torque Controllability	Feedback Sensor
TRIAC Control	Universal/DC	No Torque Control	Not Required
PWM Chopper Control	Universal / DC	No Torque Control	Not Required
V/F Control	AC	Poor Dynamic Torque Control	Not Required
Trapezoidal Drive Control	BLDC	High-Harmonics loss, High Torque Ripple	Hall Sensor
Sinusoidal Drive Control	PMSM, AC	Low – Harmonics loss, Low- Torque Ripple	Hall Sensor, Encoder
Vector Control	PMSM, AC Servomotor	Low Harmonic loss, low torque ripple	Hall Sensor, Encoder
Sensorless Trapezoidal Drive Control	BLDC	High harmonic loss, High torque ripple	Not required
Sensorless Vector Control	PMSM, AC Servomotor	Low harmonic loss, low torque ripple	Not Required

5.2. VECTOR CONTROL

Over the past decade, research into the high-performance control of brushless DC motors and permanent magnet synchronous motors has focused on two competing methodologies: Field Oriented Control (FOC) and Direct Torque Control (DTC). Both FOC and DTC are forms of vector control and aim to effectively control certain motor parameters directlyin order to force the motor to the application setting regardless of external conditions. Each methodology claim superiority over the other and each method (in terms of performance) is superior to DC motor control methods (scalar control). However, each control strategy does have distinct advantages and disadvantages which need to be considered.

5.3. FIELD ORIENTED CONTROL OF SERVOMOTOR

Field-Oriented Control (FOC), also known as vector control, is a technique used to control Permanent Magnet Synchronous Motor (PMSM) and AC induction motors (ACIM) and also servomotors. FOC provides good control capability over the full torque and speed ranges. The FOC implementation requires transformation of stator currents from the stationary reference frame to the rotor flux reference frame (also known as *d-q* reference frame).

Speed control and torque control are the most commonly used control modes of FOC. The position control mode is less common. Most of the traction applications use the torque control mode in which the motor control system follows a reference torque value. In the speed control mode, the motor controller follows a reference speed value and generates a torque reference for the torque control that forms an inner subsystem. In the position control mode, the speed controller forms the inner subsystem.

FOC algorithm implementation requires real time feedback of the currents and rotor position. Measure the current and position by using sensors. You can also use sensorless techniques that use the estimated feedback values instead of the actual sensor-based measurements.

1. The flux-producing current otherwise called field flux current (d-axis current I_{ds}) mustalways have a 90-degree space angle with the torque-producing current (q-axis current I_{qs}).

2. Both the flux-producing current (d-axis current I_{ds}) and the torque-producing current(q-axis current I_{qs}) should be independently control.

3. The torque-producing current (q-axis current I_{qs}) should be controlled at each step.

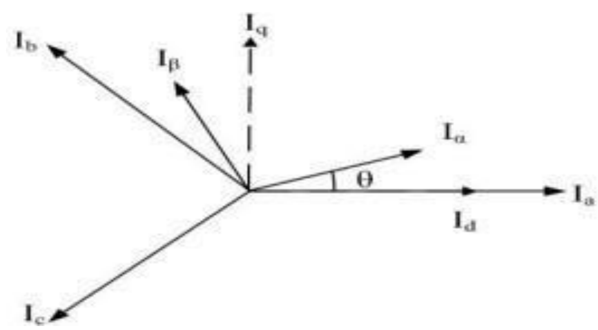


Fig. 5.2 Current Vector Representation of Servomotor

In servomotor, the measurement of three-phase stator current is done by using current sensors. The Fig. 5.2 represents the vector representation of current in ABC, αβ and dq. In order to control the speed and torque of motor the following requirements are needed to implement for Field Oriented Control of servomotor.

5.3.1. FORWARD CLARKE TRANSFORMATION

Using a Clarke transformation, the three-phase currents are transposed from the stator's three-axis system to a two-axis coordinate system as shown in Fig. 5.3. I_a, I_b and I_c stator currents are 120° phase shift to each other, whereas Iα and Iβ currents are rotating with 90° phase shift.

$$I_\alpha = I_a$$

$$I_\beta = \frac{1}{\sqrt{3}} i_\alpha + \frac{2}{\sqrt{3}} i_\beta$$

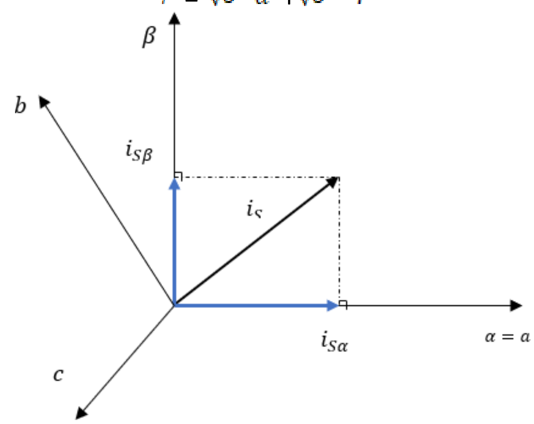


Fig. 5.3 Phasor Representation of abc to αβ Conversion

5.3.2. FORWARD PARK TRANSFORMATION

In Park transformation, the 2-axis time variation system (α, β) is again converted to a d-q coordinate system using equation 5.1. The phasor representation of Clarke's transformation is shown in Fig. 5.4.

$$i_d = i_\alpha \cos\theta + i_\beta \sin\theta$$

$$i_q = -i_\alpha \sin\theta + i_\beta \cos\theta \qquad (5.1)$$

The d-axis and q- axis are perpendicular to each where I_d current represents the flux producing current as it is followed by rotor flux φ_r and I_q current represent torque producing current. Controlling these two currents by using current controller and flux controller with the help of PI speed and torque are controlled.

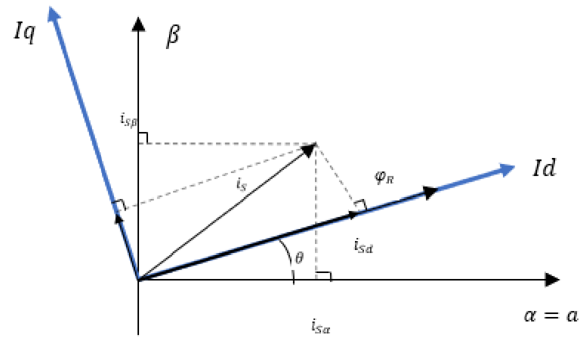


Fig. 5.4 Phasor Representation of αβ to dq Conversion

5.3.3. INVERSE PARK TRANSFORMATION

The I_d and I_q current from the park transformation is given to the current controller and speed controller block in vector, and from that V_d and V_q axis voltage is obtained. This V_d and V_q voltage is converted into V_α and V_β *and* which is given as the input to the pulse width modulation block for generating the gate pulse for the inverter. Eqn. 5.2. represents the inverse park transformation.

$$V_\alpha = V_d \cos\theta - V_q \sin\theta$$

$$V_\beta = V_d \sin\theta + V_q \cos\theta \qquad (5.2)$$

5.4. MODULATION TECHNIQUES

The most popular modulation technique used in inverters is pulse width modulation (PWM) and the inverters that use this technique are called PWM inverters. PWM inverters eliminate lower order harmonics and decrease the THD content in the output AC voltage. They also minimize filter requirements. The types of modulation commonly used in inverters are

1. Single Pulse Modulation
2. Multiple Pulse Modulation
3. Sinusoidal PWM
4. Space Vector Modulation

Space vector modulation (SVM) stands out as the preferred choice for pulse width modulation (PWM) techniques due to its efficiency in minimizing harmonic distortion and maximizing the utilization of the DC link voltage in power converters. Compared to other PWM methods like sinusoidal modulation, SVM offers superior performance in terms of harmonic content reduction and improved output waveform quality, making it ideal for applications requiring high quality voltage output with minimal distortion, such as motor drives and renewable energy systems. Compared to other PWM methods like sinusoidal modulation, SVM offers superior performance in terms of harmonic content reduction and improved output waveform quality, making it ideal for applications requiring high-quality voltage output with minimal distortion, such as motor drives and renewable energy systems.

5.5. SPACE VECTOR PULSE WIDTH MODULATION

Space vector modulation (SVM) is a common technique in field oriented control for induction motors and permanent magnet synchronous motors (PMSM). Space vector modulation improves dc bus utilization by 15.15%, further digital implementation of this scheme is easier. The SVPWM method of generating the pulsed signals minimizes the harmonic contents. Note that the harmonic contents determine the copper losses of the machine which account for a major portion of the machine losses. Taking into consideration the two constraints quoted above there are eight possible combinations for the switch commands. The Fig.5.5. explains the sectors of SVPWM.

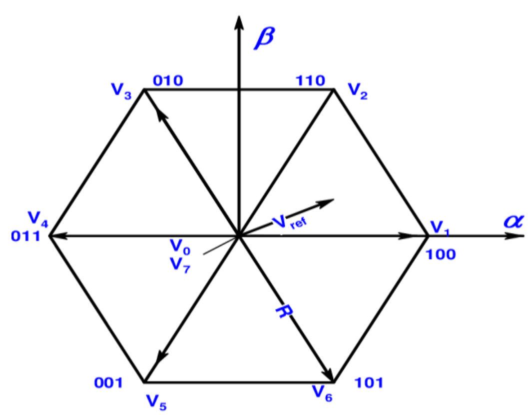


Fig. 5.5 Sector of SVPWM

The vectors divide the plan into six sectors. Depending on the sector that the voltage reference is in, two adjacent vectors are chosen which is shown in Fig. 5.6. The binary representations of two adjacent basic vectors differ in only one bit, so that only one of the upper transistors switches when the switching pattern moves from one vector to the adjacent one. The two vectors are time weighted in a sample period T to produce the desired output voltage.

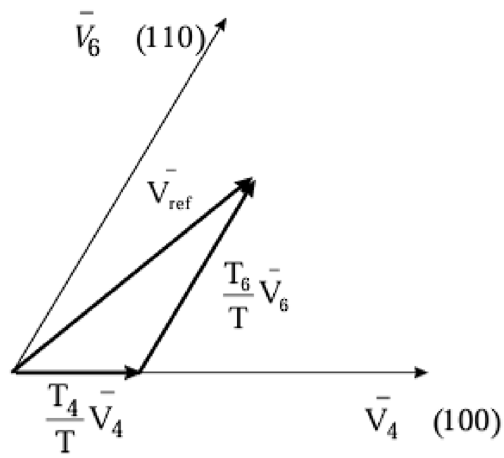


Fig. 5.6 Reference Vector Selection

Where T4 and T6 are the times during which the vectors V4, V6 are applied and T0 the time during which the zero vectors are applied. When the reference voltage (output of the Inverse Park transformation) and the sample periods are known, the following system makes it possible to determine the uncertainties T4, T6 and T0. The generated space vector PWM waveforms are symmetrical with respect to the middle each PWM period. The Fig. 5.7 shows the waveforms of SVPWM in the sector 3.

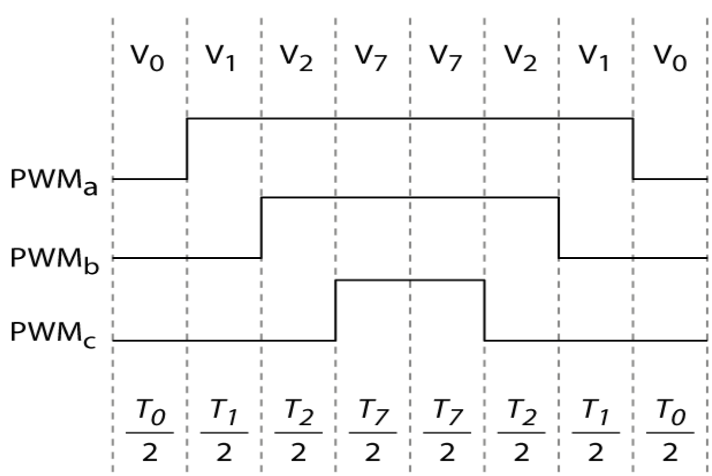


Fig. 5.7 Switching Pattern in Sector 3

The following Fig. 5.8. shows the pattern of SVPWM for each sector:

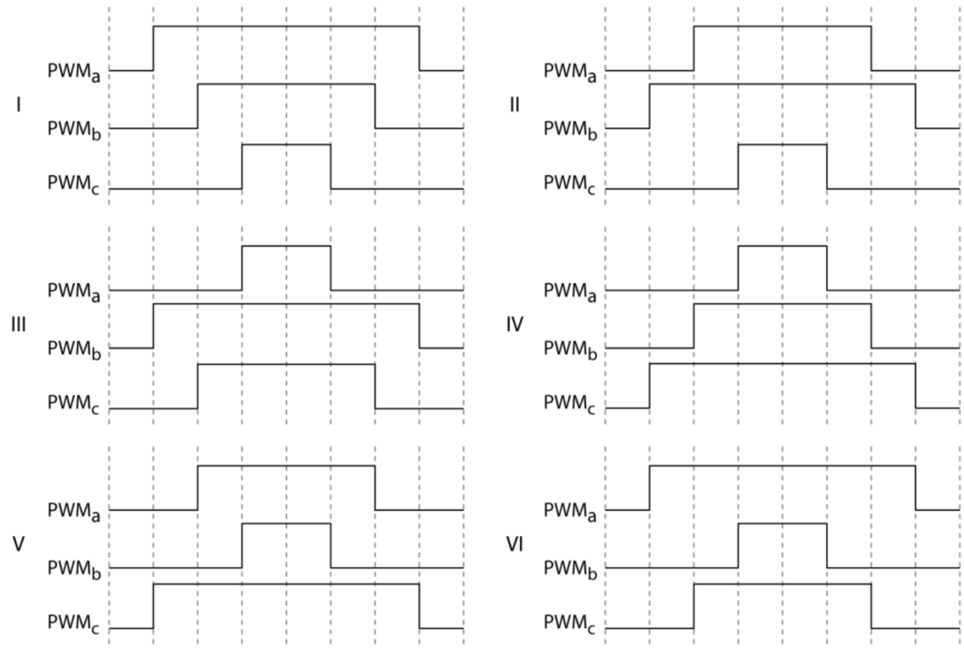


Fig. 5.8 Switching Pattern of each sector

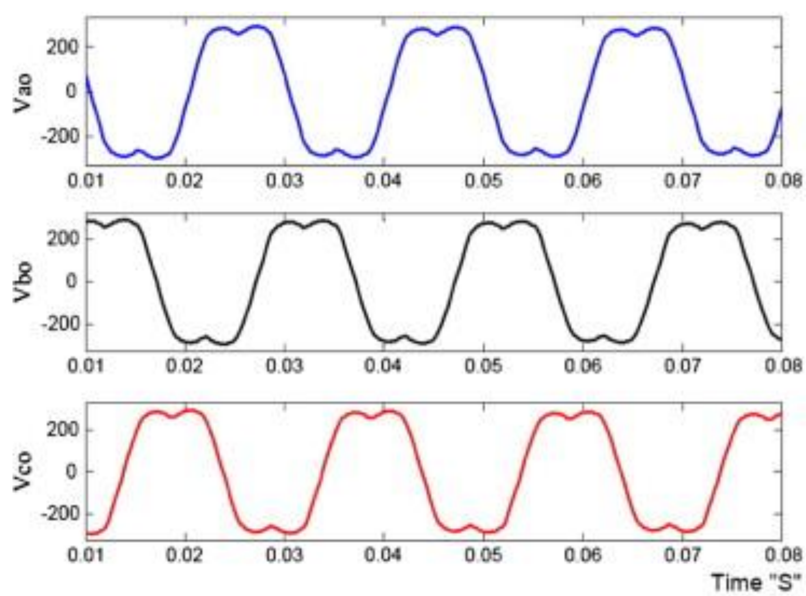


Fig. 5.9 Reference wave of SVPWM

The Fig. 5.9 shows the reference wave of Phase A, B, C generated from Space Vector Pulse Width Modulation. By the use of this reference wave SVPWM improves dc bus utilization by 15.15%.

CHAPTER 6
PROPOSED METHODOLOGY

This chapter explains the Field oriented Control with PI control and Fuzzy Logic Controller for the servodrive.

6.1. FIELD ORIENTED CONTROL WITH PI CONTROLLER

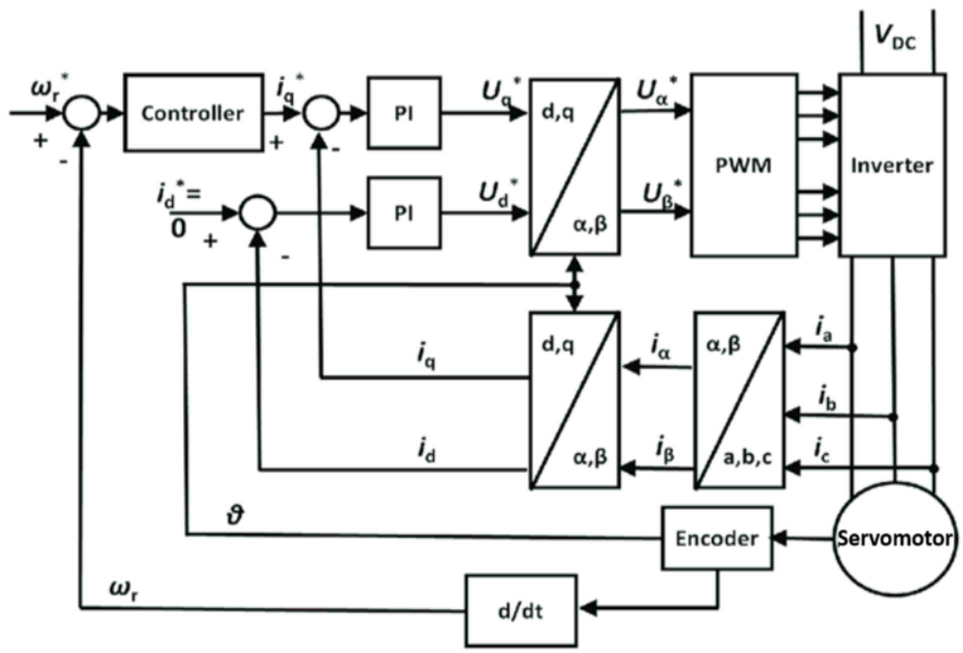


Fig. 6.1 Block Diagram of Servodrive with PI Controller

The Fig. 6.1 represents the generalized block representation of the servomotor drive with PI controller. With FOC, two PI current controllers can be used to control both aspects of the motor current vector separately. One current controller (Iq) is used to control the motor's torque and is thereby called the torque controller; the other one (Id) controls the magnetic flux inside the motor. Transformations are based on the actual rotor angle, which is acquired by position sensors like Hall sensors or encoders. The magnetic flux is mainly generated by the rotor, so the reference value of Id is usually zero.

6.1.1. SPEED CONTROLLER

In Field-Oriented Control (FOC) of electric motors, the speed controller plays a crucial role in regulating the motor's speed. The speed controller typically employs a proportional-integral (PI) control algorithm, although other control strategies like proportional-integral-derivative (PID) control or advanced techniques such as model predictive control (MPC) can also be used depending on the application requirements.

1. **Speed Error Calculation**: The first step in the speed control loop is calculating the speed error, which is the difference between the desired reference speed and the actual speed of the motor. The reference speed can be set externally by a user or generated by a higher-level control system.

2. **Proportional and Integral Terms**: The speed controller typically consists of two main components: the proportional (P) term and the integral (I) term. The proportional term provides a control action proportional to the speed error, aiming to reduce the error quickly. The integral term integrates the speed error over time and helps eliminate any steady-state error, ensuring that the motor achieves and maintains the desired speed.

3. **Controller Output**: The output of the speed controller is the control signal that determines the torque command sent to the motor. This torque command is then converted into appropriate current references for the dq axis of the motor using inverse Park and inverse Clarke transformations.

4. **Controller Tuning**: Proper tuning of the speed controller parameters (proportional gain, integral gain) is crucial for achieving stable and responsive speed control. Tuning involves adjusting these parameters to balance between achieving fast response to speed changes and maintaining stability without excessive oscillations or overshoot.

5. **Limiting**: The output of the speed controller may need to be limited to prevent excessive torque commands that could potentially damage the motor or drive system. Limiting the controller output ensures that the torque commands remain within safe operating limits.

6.1.2. FLUX CONTROLLER

1. **Reference Flux Generation:** The desired flux reference is generated based on the user's input or control requirements.
2. **Flux Error Calculation:** The difference between the desired reference flux and the actual measured flux is calculated. This error represents the deviation of the motor's magnetic field from the desired value.
3. **Controller Output:** The output of the flux controller provides the voltage references for the motor's q-axis (axis aligned with the magnetic field). These voltage references determine the q-axis current required to control the flux.

6.1.3. TORQUE CONTROLLER

1. **Reference Torque Generation:** The desired torque reference is generated based on the user's input or control requirements.
2. **Torque Error Calculation:** The difference between the desired reference torque and the actual measured torque is calculated. This error represents the deviation of the motor's torque from the desired value.
3. **Controller Output:** The output of the torque controller provides the voltage references for the motor's d-axis (axis perpendicular to the magnetic field). These voltage references determine the d-axis current required to control the torque.

In summary, the motor's flux can be controlled by the direct-axis current (Id) without affecting the torque, and the torque can be controlled by the quadrature-axis current (Iq) without affecting the flux. This decoupling is a key advantage of Field Oriented Control (FOC).

6.2. FIELD ORIENTED CONTROL WITH FUZZY LOGIC CONTROLLER

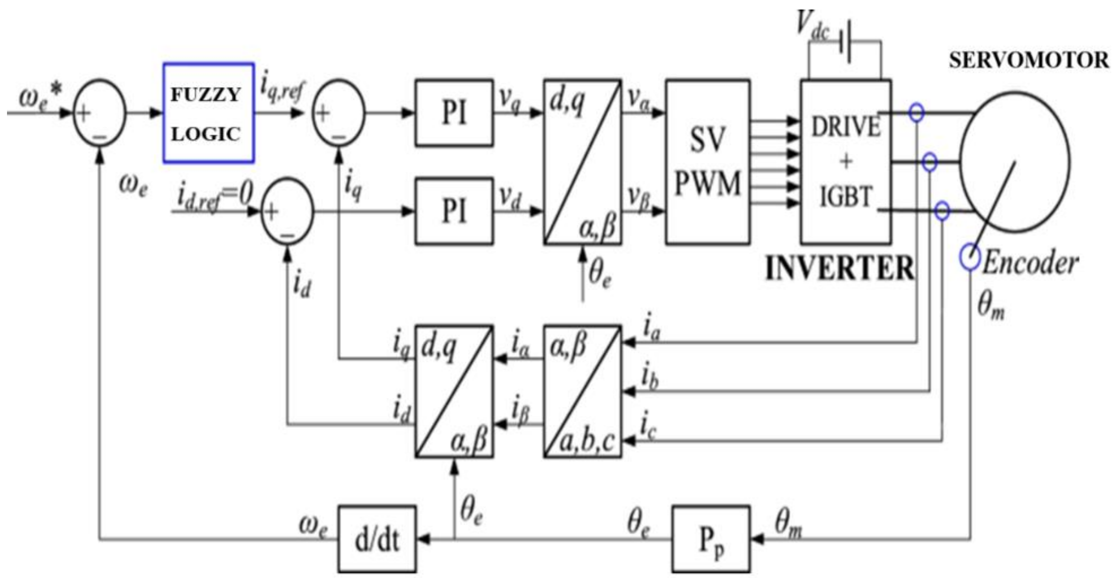


Fig. 6.2 Block Diagram of Servodrive with Fuzzy Logic - PI Controller

The Fig. 6.2 represents the generalized block representation of the servomotor drive with Fuzzy Logic controller. Fuzzy Logic is a multi-valued logic in which the truth values of variables vary between 0 and 1. In contrast, the traditional logic uses only values true and false. It is applied in context of imprecise information to determine the representation of blurriness and uncertainty in decision making. It is used to handle the, unreliable information and is a mathematical method that is used for representing indistinctness and unsteadiness in decision making. Fuzzy Logic is used in diversified domains including the control systems, image processing, natural language processing, medical diagnosis, AI and so on.

In summary, fuzzy Logic is a mathematical technique for representing uncertainty in decision-making. It allows for partial truths and find application in numerous fields. It is based on the concept of a membership function and it is realized by the use of Fuzzy rules. In the boolean system, the concept of truth value is defined by 1. 0 stands for absolute truth value and 0. Within the fuzzy system there is no logic for the absolute truth and the absolute false value. However, in fuzzy logic the third value is available which is neither fully false nor fully true.

6.2.1. FUZZY LOGIC ARCHITECTURE

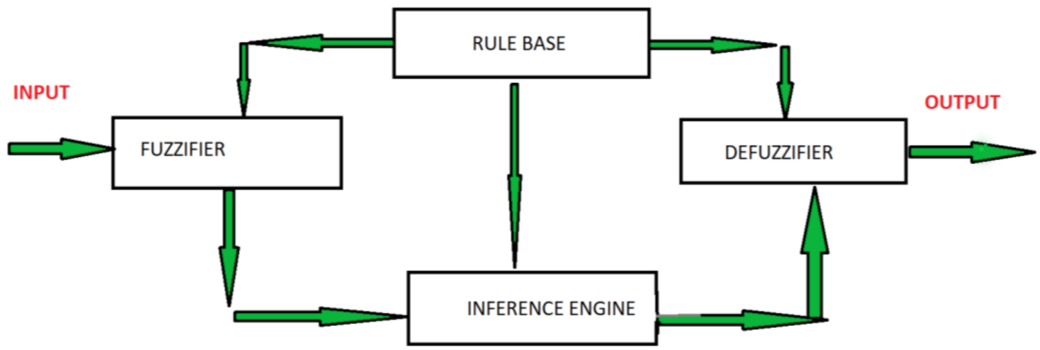


Fig. 6.3 Fuzzy Interference System Architecture

Fuzzy inference is a method that interprets the values in the input vector and, based on some sets of rules, assigns values to the output vector which is shown in Fig. 6.3 In fuzzy logic, the truth of any statement becomes a matter of a degree.

- **FUZZIFICATION:** It is used to convert inputs i.e. crisp numbers into fuzzy sets. Crisp inputs are basically the exact inputs measured by sensors and passed into the control system for processing, such as temperature, pressure, rpm etc.
- **RULE BASE:** It contains the set of rules and the IF-THEN conditions provided by the experts to govern the decision-making system, on the basis of linguistic information. Recent developments in fuzzy theory offer several effective methods for the design and tuning of fuzzy controllers. Most of these developments reduce the number of fuzzy rules.
- **INFERENCE ENGINE:** It determines the matching degree of the current fuzzy input with respect to each rule and decides which rules are to be fired according to the input field. Next, the fired rules are combined to form the control actions.
- **DEFUZZIFICATION:** It is used to convert the fuzzy sets obtained by the inference engine into a crisp value. There are several defuzzification methods available and the best-suited one is used with a specific expert system to reduce the error.

CHAPTER 7

SIMULATION AND RESULTS

This chapter discuss about the analysis of Field Oriented Control of servomotor using PI controller and Fuzzy Logic Controller using MATLAB/Simulink. The Table 7.1 indicates the rated speed of 3000 rpm with the rated power of 2.07 kW for servomotor is taken.

Table 7.1 System Parameter of Servomotor

Parameter	Values
Supply Voltage	200 V
Power	2.07 kW
Motor Poles	8
Speed	3000 rpm
Torque	7 N-m

7.1. FIELD ORIENTED CONTROL WITH PI CONTROLLER

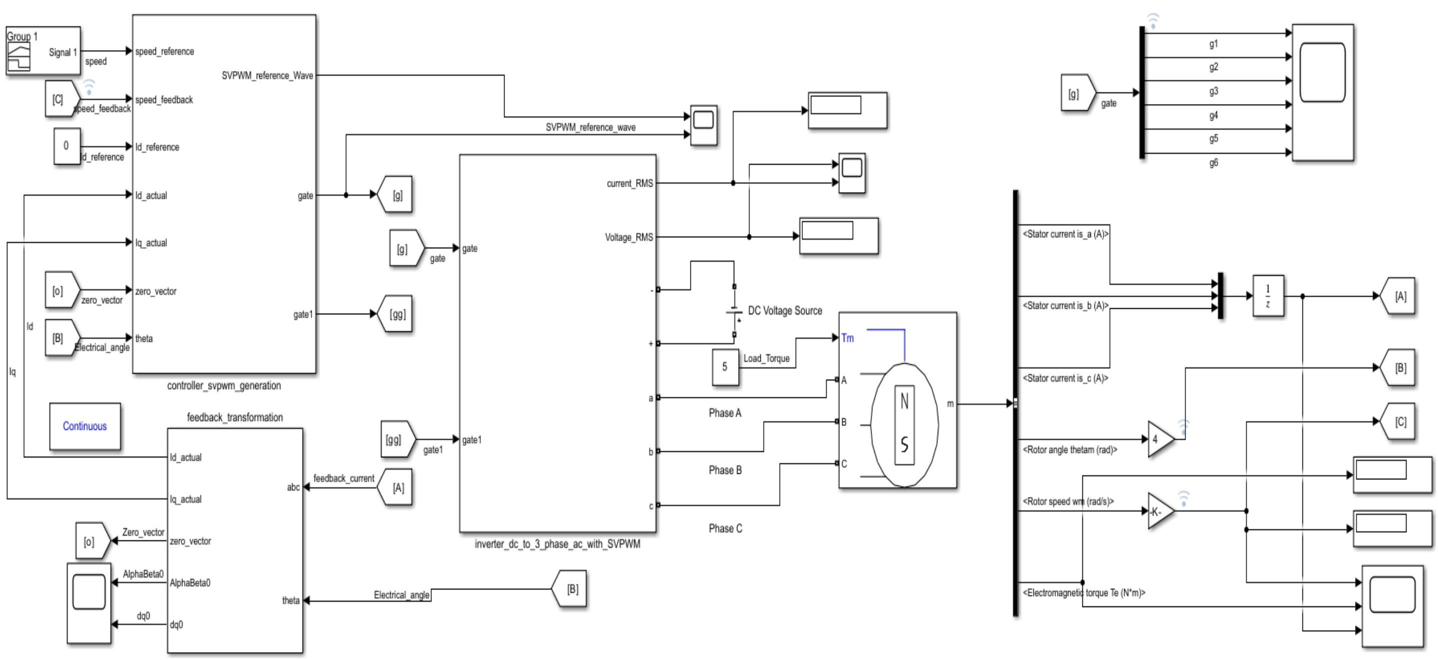


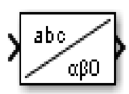
Fig. 7.1 Simulink model of PI control of Servodrive

The Fig. 7.1 shows the MATLAB/Simulink model of Field Oriented Control of servodrive with PI controller. The three motor currents is taken as feedback for the Clarke's transformation and Park's transformation.

7.2. DESCRIPTION OF MATLAB BLOCKSETS

7.2.1. ABC TO αβ0 CONVERSION BLOCK

The abc to Alpha-Beta-Zero block performs a Clarke transform on a three-phase abc signal by using the matrix equations shown in Fig. 7.2.

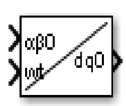


$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}$$

Fig. 7.2 abc to αβ0 conversion

7.2.2. αβ0 TO DQ0 CONVERSION BLOCK

The Alpha-Beta-Zero to dq0 block performs a transformation of αβ0 Clarke components in a fixed reference frame to dq0 Park components in a rotating reference frame using the matrix equations shown in Fig. 7.3.



$$\begin{bmatrix} u_d \\ u_q \\ u_0 \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) & 0 \\ -\sin(\omega t) & \cos(\omega t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix}$$

Fig. 7.3 αβ0 to dq0 conversion

7.2.3. SIGNAL BUILDER BLOCK

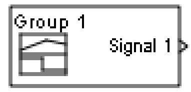


Fig. 7.4 Signal Builder

The Signal Builder block shown in Fig. 7.4 allows you to create interchangeable groups of piecewise linear signal sources and use them in a model. The reference speed for the model is given using Signal Builder block which is shown in Fig. 7.5.

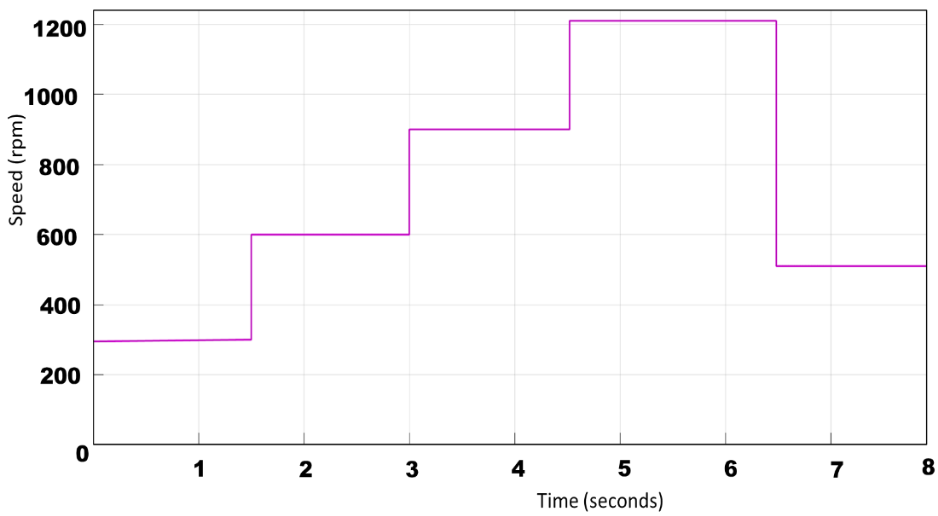


Fig. 7.5 Signal Builder Block Input

7.2.4. PID CONTROLLER BLOCK

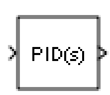


Fig. 7.6 PID controller

The PID Controller block shown in Fig. 7.6 implements a PID controller (PID, PI, PD, P only, or I only). The input of the block is typically an error signal, which is the difference between a reference signal and the system output. The block output is a weighted sum of the input signal, the integral of the input signal, and the derivative of the input signal.

7.2.5. FUZZY LOGIC CONTROLLER BLOCK

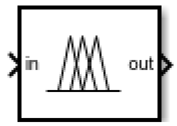


Fig. 7.7 Fuzzy Logic Controller

The Fuzzy Logic Controller block shown in Fig.7.7 implements a fuzzy inference system (FIS) in Simulink. For a single-input fuzzy inference system, the input is a scalar signal. For a multi-input fuzzy system, combine the inputs into a vector signal using MUX block. In this Mamdani max-min Fuzzy Interference System is used. In a Mamdani system, the output of each rule is a fuzzy set.

7.3. FIELD ORIENTED CONTROL WITH FUZZY LOGIC CONTROLLER

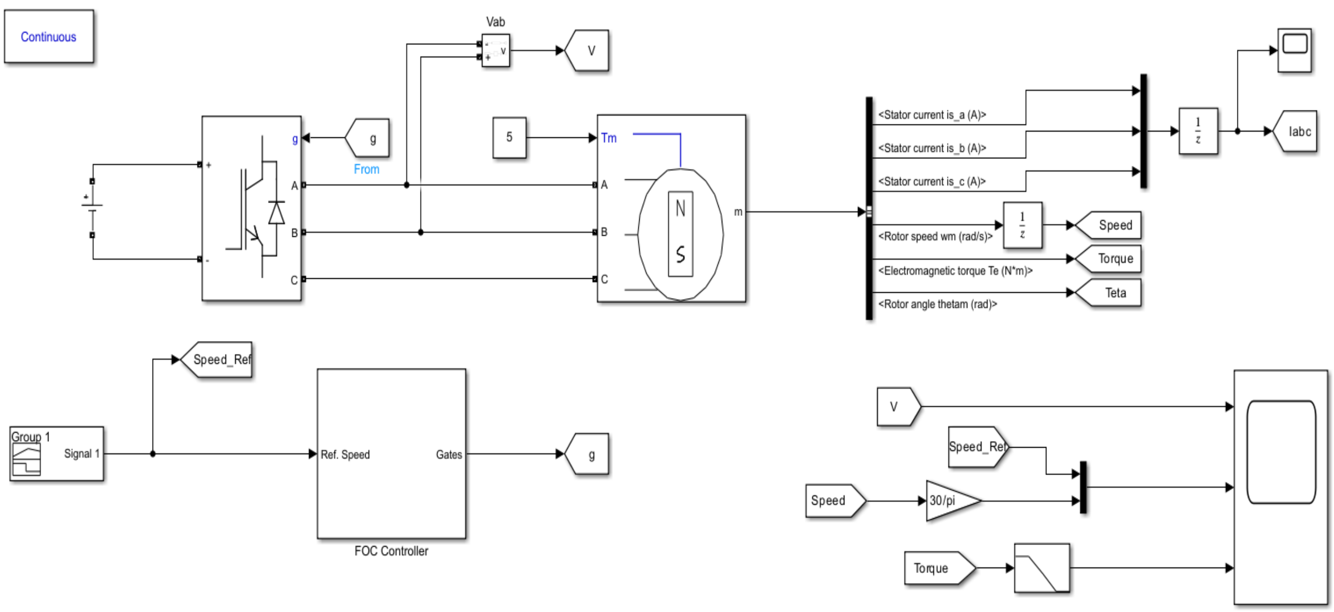


Fig. 7.8 Simulink model of Fuzzy Logic Control of Servodrive

The Fig. 7.8 shows the MATLAB/Simulink model of Field Oriented Control of servodrive with fuzzy logic controller. The three motor currents is taken as feedback for the Clarke's transformation and Park's transformation. The reference speed for the model is given using Signal Builder block which is shown in Fig. 7.5.

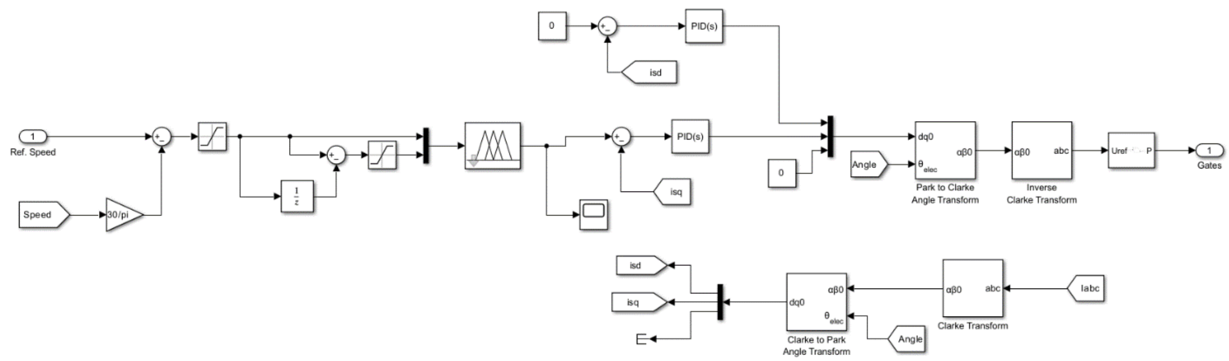


Fig. 7.9 Fuzzy Logic Controller Integration

The Fig. 7.9 shows the fuzzy logic controller integration in the Speed Control loop of FOC. The error due to speed (called "error"), change in speed error (called "CoE"), and output variable of controller (called "Output") are the three input and output variables of the controller. They may be defined as follows: error = CoE = Output = {NH, NM, NL, ZE, PL, PM, PH} which is shown in Table 7.2. The output surface of the Fuzzy Interference System is shown in Fig. 7.10.

Table 7.2 Fuzzy Logic Rules

CoE \ Error	NH	NM	NL	ZE	PL	PM	PH
NH	NH	NH	NM	NM	NL	ZE	ZE
NM	NH	NH	NM	NL	NL	ZE	PL
NL	NM	NM	NM	NL	ZE	PL	PL
ZE	NM	NM	NL	ZE	PL	PM	PM
PL	NL	NL	ZE	PL	PL	PM	PM
PM	NL	ZE	PL	PM	PM	PM	PH
PH	NH	NM	NL	ZE	PL	PM	PH

The Fuzzy Logic controller has the two inputs: error and change of error (CoE). The variables for error, CoE, and output include: NH (Negative High), NM (Negative Medium), NL (Negative Low), ZE (Zero Error), PL (Positive Low), PM (Positive Medium), and PH (Positive High). Each combination of these variables maps to a specific rule guiding the controller's response.

7.4. INFERENCE FROM THE FUZZY LOGIC RULE TABLE

1. **When both Error and CoE are High or Low**:
   - **NH Error and NH CoE**: When both the error and change of error are very large and negative, the output is also NH. This indicates that a strong corrective action is required to bring the speed back to the reference.
   - **PH Error and PH CoE**: When both the error and change of error are very large and positive, the output is PH. This indicates a strong corrective action in the opposite direction to reduce the error quickly.
2. **When Error is Zero**:
   - **ZE (Zero) Error**: When the error is zero, meaning the actual speed matches the reference speed, the output depends mainly on CoE.
   - **Negative CoE (e.g., NM, NL)**: If the error is zero but the CoE is negative (indicating the error was positive and is reducing), the controller will take actions to prevent overshooting the desired speed.
   - **Positive CoE (e.g., PM, PH)**: If the error is zero but CoE is positive (indicating the error was negative and is increasing), the controller will take actions to prevent the speed from dropping below the desired value.
3. **Error and CoE are Mixed**:
   - **NH Error and PM CoE**: When the error is very negative but the CoE is positive medium, it indicates the system is correcting itself but slowly. The output will be adjusted to continue reducing the error without causing instability.
   - **PH Error and NM CoE**: When the error is very positive but the CoE is negative medium, it shows the system is moving towards correcting itself. The output will aim to assist in this correction smoothly.

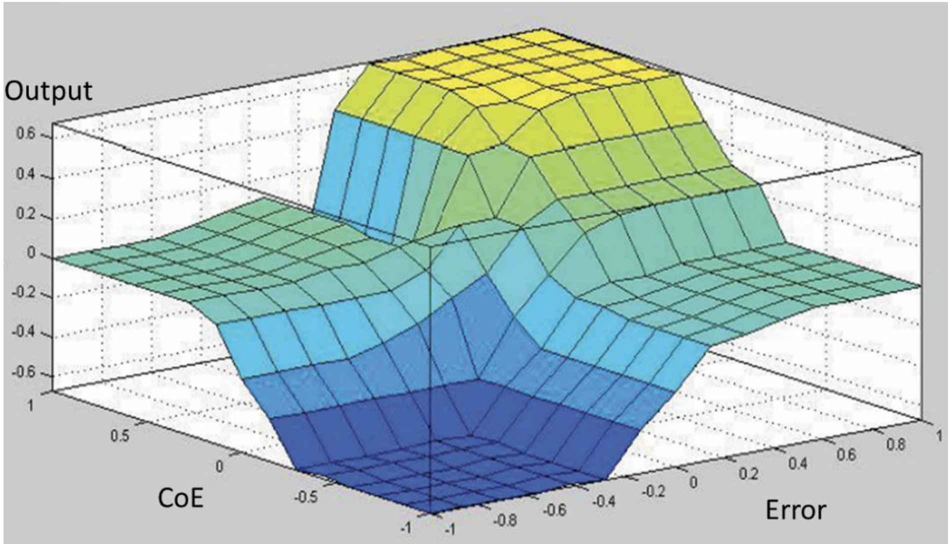


Fig. 7.10 Output Surface of Fuzzy Interference System

7.5. RESULTS AND DISCUSSIONS

Based on the simulation made for field-oriented control of servomotor using PI controller and Fuzzy Logic Controller, the results are compared and analyzed for variable speed conditions by using Signal Builder Block.

7.5.1. OUTPUT SPEED RESPONSE

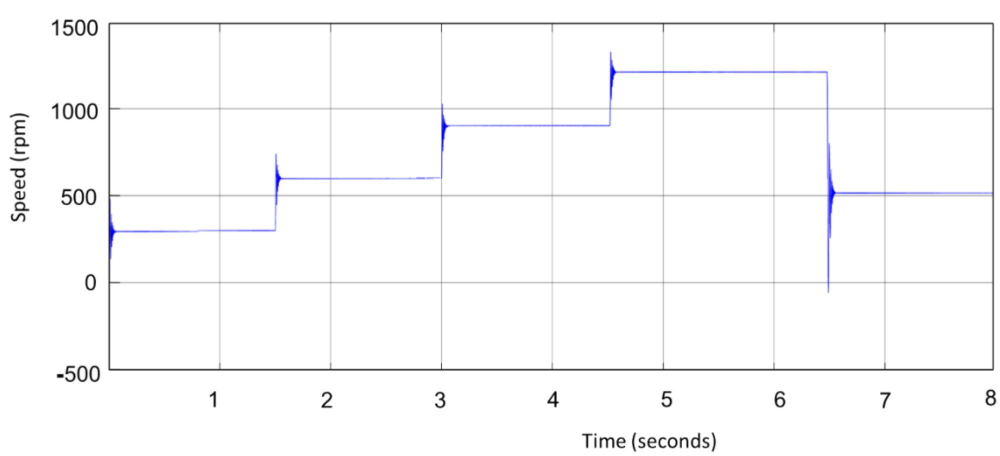


Fig. 7.11 Output Speed waveform using PI controller

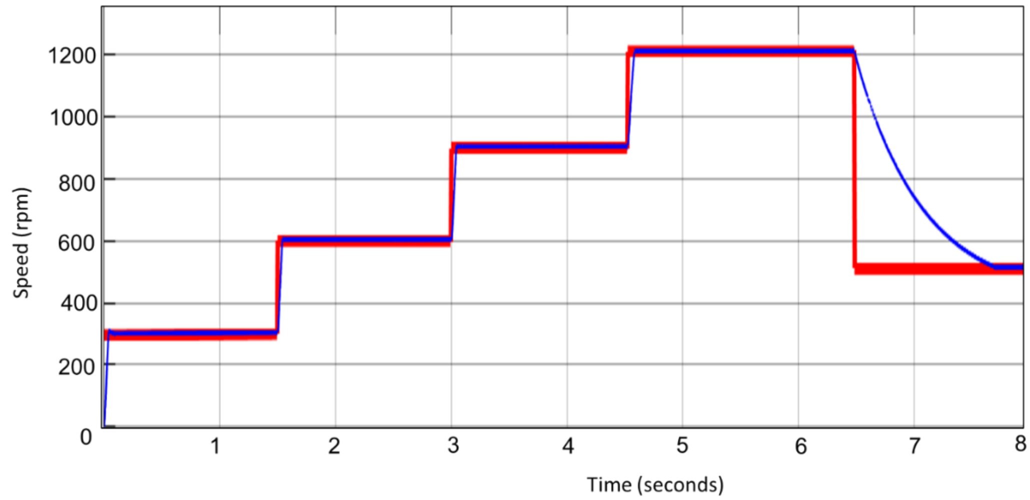


Fig. 7.12 Output Speed waveform using Fuzzy Logic controller

The Fig. 7.11 and Fig. 7.12 shows the output speed waveform of the model using PI controller and Fuzzy Logic controller. The Fuzzy logic controller output speed response has no overshoot or ripples in the transient period and the overall response is better than PI controller.

7.5.2. TRANSIENT SPEED RESPONSE

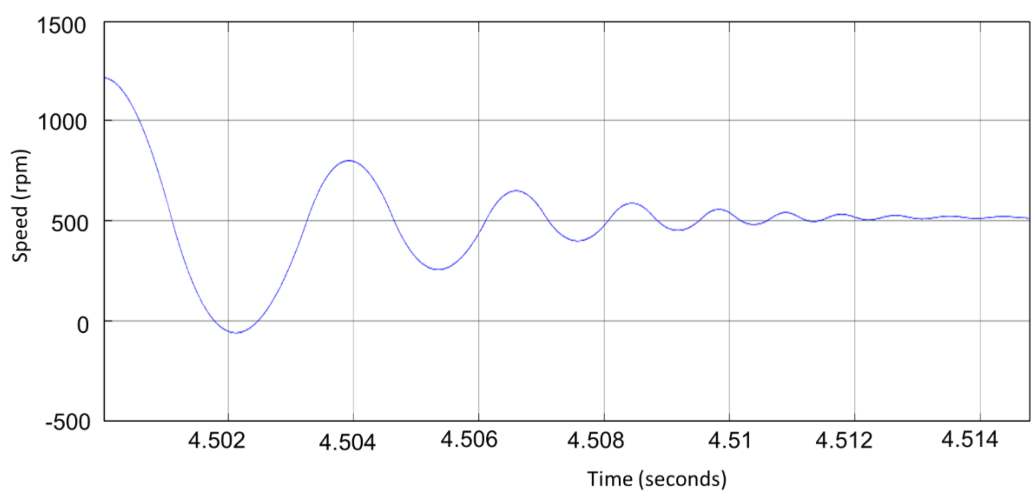


Fig. 7.13 Transient Speed waveform using PI controller

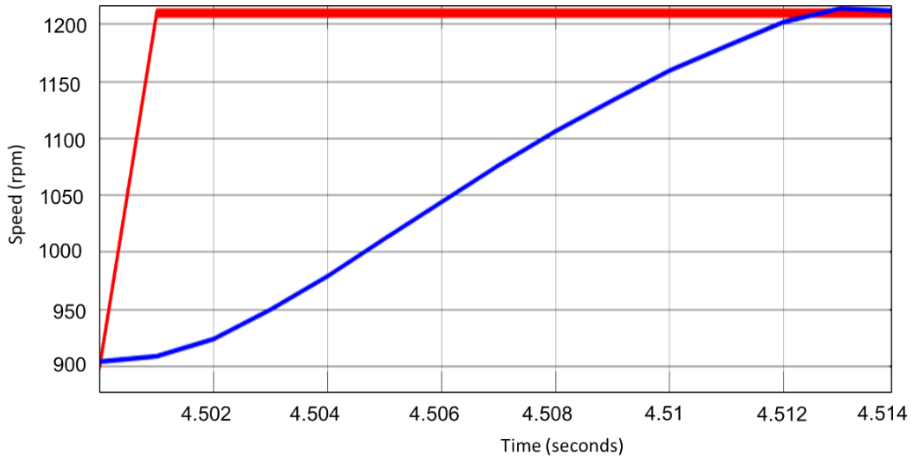


Fig. 7.14 Transient Speed waveform using Fuzzy Logic controller

The Fig. 7.13 and Fig. 7.14 shows the transient speed waveform of the model using PI controller and Fuzzy Logic controller. The Fuzzy logic controller transient speed response is similar to the critical damped response. The PI controller transient speed response is similar to the underdamped response. In most of the applications, the critical damped response is preferred.

7.5.3. OUTPUT TORQUE RESPONSE

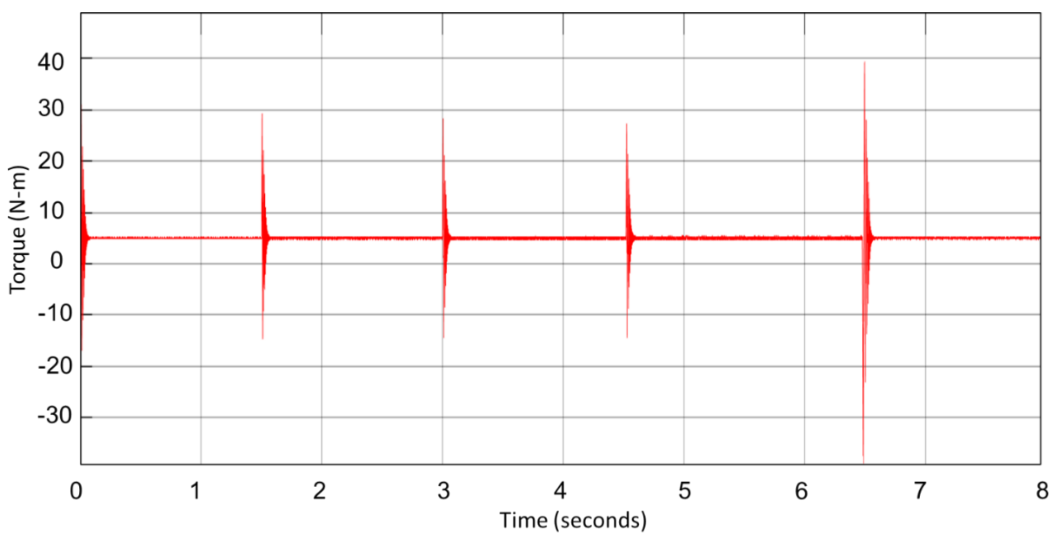


Fig. 7.15 Output Torque waveform using PI controller

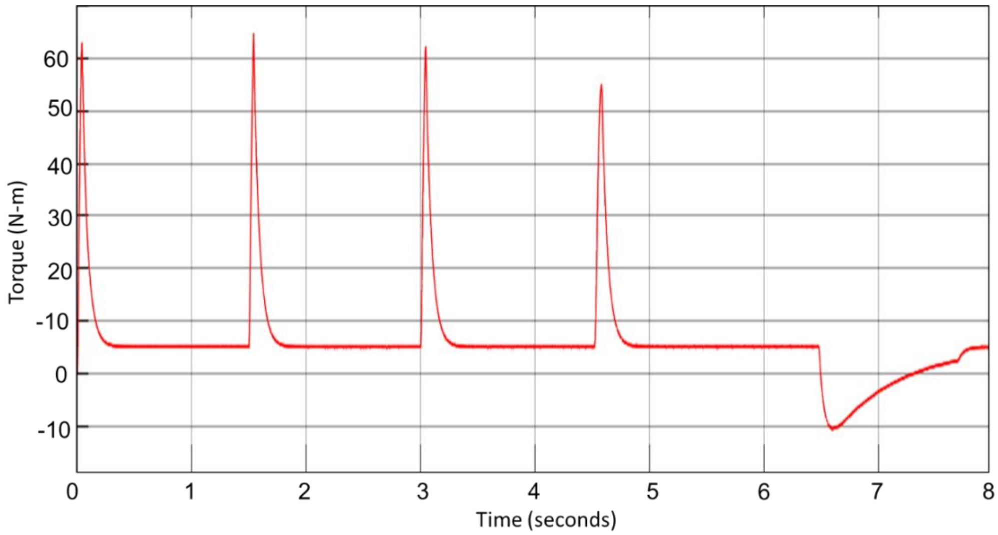


Fig. 7.16 Output Torque waveform using Fuzzy Logic controller

The Fig. 7.15 and Fig. 7.16 shows the output torque waveform of the model using PI controller and Fuzzy Logic controller. The Fuzzy logic controller output torque response has no torque ripples in steady state period is less than the PI controller.

7.5.4. TRANSIENT TORQUE RESPONSE

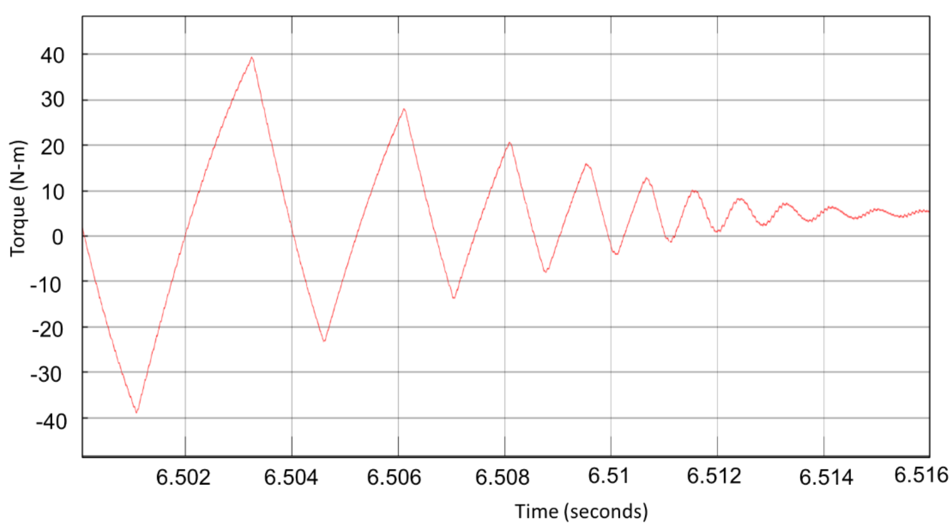


Fig. 7.17 Transient Torque waveform using PI controller

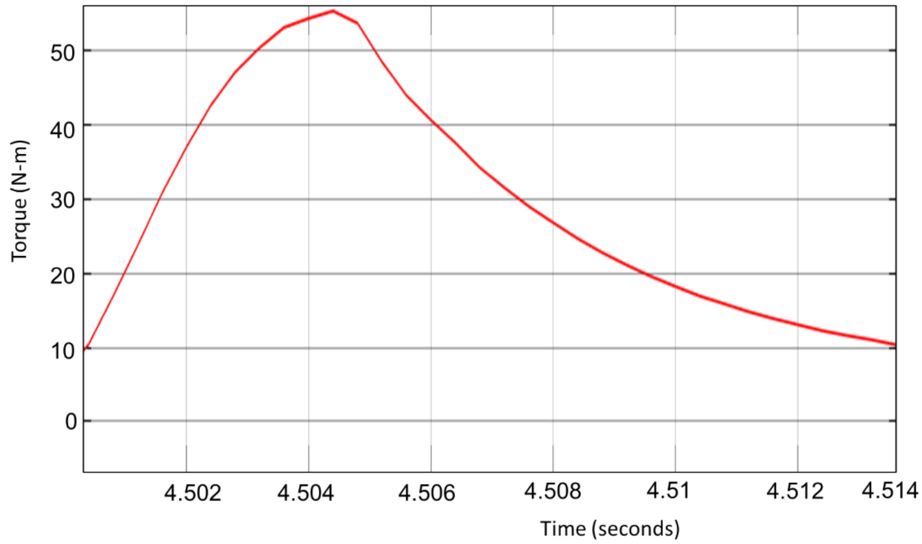


Fig. 7.18 Transient Torque waveform using Fuzzy Logic controller

The Fig. 7.17 and Fig. 7.18 shows the transient torque waveform of the model using PI controller and Fuzzy Logic controller. The PI controller transient torque response has more positive and negative overshoot ripples and the settling time is higher than the Fuzzy Logic controller.

7.5.5. THREE PHASE INPUT CURRENT

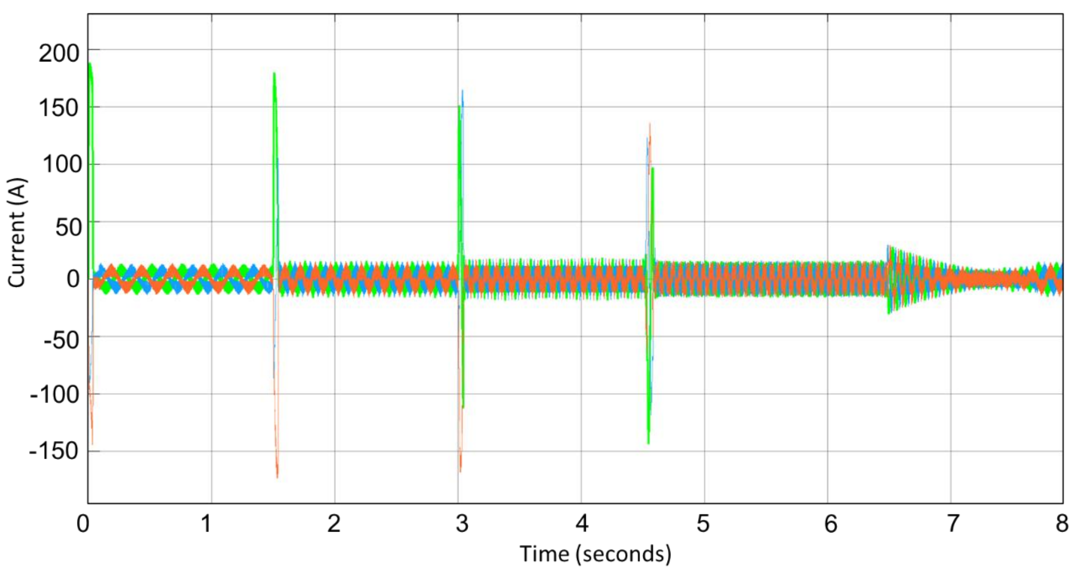


Fig. 7.19 Three Phase Input Current waveform using PI controller

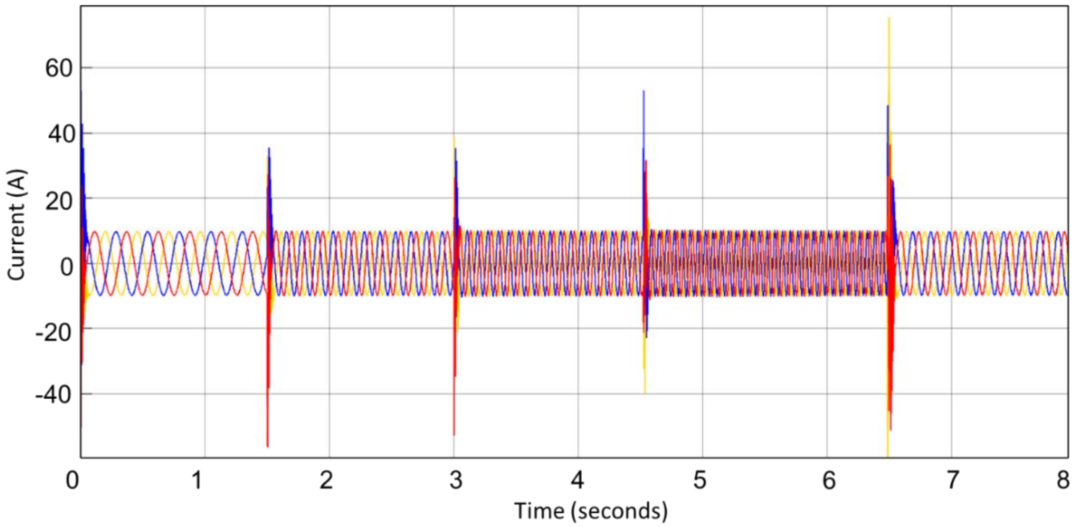


Fig.7.20 Three Phase Input Current waveform using Fuzzy Logic controller

The Fig. 7.19 and Fig. 7.20 shows the three phase input current waveform of the model using PI controller and Fuzzy Logic controller. The three phase input current of the Fuzzy logic controller is more sinusoidal than the PI controller.

CHAPTER 8
CONCLUSION

8.1. CONCLUSION

In conclusion, the utilization of servo drives in welding applications facilitates the precise control necessary for producing strong and clean welds, a task that cannot be consistently achieved by human operators alone. By integrating the designed servo drive into robotic welding systems, the project enables the maintenance of a high level of precision and repeatability in the welding process. This ensures reliable and uniform weld quality, which is essential for the consistent and efficient operation of robotic welding applications.

The project aims to design a servo drive input of single-phase AC voltage into a three-phase AC output, which is essential for powering the low power servo motors used in robotic welding applications. The torque and speed response characteristics of the servo drive were fine-tuned to ensure its suitability for low-power robotic applications, where precise control of the servo motor is crucial. It also involves comparing the performance of a PI controller and a Fuzzy Logic Controller for Field Oriented Control using MATLAB/Simulink. The results demonstrated that the Fuzzy Logic Controller outperformed the PI controller, it shows the advantages of advanced control techniques in optimizing the servo drive's output speed and torque response.

8.2. FUTURE SCOPE

Servodrives are preferred for applications where precise control over speed, position, and torque is essential. These applications often require high-performance motion control, such as in robotics, CNC machining, printing, packaging, and automated assembly lines etc. The future scope of this project work is to achieve the complete hardware implementation of experimental setup Field Oriented Control of Servomotor using PI controller and Fuzzy Logic controller.

BIBLIOGRAPHY

[1] H. M. Flieh, R. D. Lorenz, E. Totoki, S. Yamaguchi and Y. Nakamura, "Investigation of Different Servo Motor Designs for Servo Cycle Operations and Loss Minimizing Control Performance," IEEE Transactions on Industry Applications, vol. 54, no. 6, pp. 5791-5801, Nov.-Dec. 2018.

[2] Y. Yasa, E. Sahin, C. Acar, A. Gozutok, E. Firat and E. Mese, "Servo motor driver design for high performance applications," 3rd International Conference on Electric Power and Energy Conversion Systems, Istanbul, Turkey, 2013, pp. 1-6.

[3] S. Lee, C. Hwang, J. Shim and J. Ha, "A Control Method of Servo Motor Drives for Fast Dynamic Response and Low Torque Ripple," 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022, pp. 01-05, doi: 10.1109/ECCE50734.2022.9947638.

[4] H. J. van de Straete, P. Degezelle, J. De Schutter and R. J. M. Belmans, "Servo motor selection criterion for mechatronic applications," IEEE/ASME Transactions on Mechatronics, vol. 3, no. 1, pp. 43-50, March 1998.

[5] M. Md Kamal and N. Mamat, "Controller design for Servo Motor," IEEE Symposium on Industrial Electronics & Applications, Kuala Lumpur, Malaysia, 2009, pp. 926-929.

[6] A. K. Chakraborty and N. Sharma, "Control of permanent magnet synchronous motor (PMSM) using vector control approach," 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), Dallas, TX, USA, 2016.

[7] Gupta, B. Singh, and C. Choudhury, "Comparative Analysis of Fuzzy Logic and PI Controller for Field-Oriented Control of PMSM," IEEE Transactions on Industrial Electronics, vol. 65, no. 8, pp. 6543-6552, 2018.

[8] B. Sonkriwal, P.R.D. and H. Tiwari, “Analysis of Sliding mode, Fuzzy PI and PI Control Strategies for Permanent Magnetic Synchronous Motor Drive,” IEEE 3rd International Conference on Sustainable Energy and Future Electric Transportation (SEFET), Bhubaneswar, India, 2023.

[9] A. Dumitrescu, D. Fodor, T. Jokinen, M. Rosu and S. Bucurenciu, "Modeling and simulation of electric drive systems using MATLAB/Simulink environments," IEEE International Electric Machines and Drives Conference. IEMDC'99. Proceedings (Cat. No.99EX272), Seattle, WA, USA, 1999, pp. 451-453.

[10] M. F. Shams, M. S. Alam, and M. A. Rahman, "Performance comparison of PI and fuzzy controllers for speed control of PMSM," IEEE International Conference on Industrial Technology, vol. 4, pp. 1707-1712, 2019.

[11] R. Rao, K. K. Jha, and S. K. Panda, "Comparative Study of PI, Fuzzy, and Neuro-Fuzzy Controllers for Field Oriented Control of PMSM," IEEE Transactions on Power Electronics, vol. 30, no. 3, pp. 1512-1523, 2015.

[12] S. Jain and N. Verma, "Comparison of Fuzzy Logic Controller and PI Controller for Speed Control of PMSM," IEEE Transactions on Industrial Informatics, vol. 14, no. 5, pp. 2267-2276, 2018.

[13] S. J. Patil and R. S. Patil, "Performance Comparison of PI and Fuzzy Controllers for Speed Control of PMSM Drive," IEEE Transactions on Power Systems, vol. 34, no. 2, pp. 1183-1194, 2019.

[14] S. R. Mishra and S. K. Gupta, "Comparison of PI and Fuzzy Logic Controllers for Speed Control of PMSM," IEEE Transactions on Control Systems Technology, vol. 28, no. 6, pp. 2397-2407, 2020.

[15] V. S. Choudhari and A. M. Kuthe, "Comparative Analysis of PI and Fuzzy Logic Controllers for Speed Control of PMSM," IEEE Transactions on Industrial Applications, vol. 50, no. 4, pp. 2257-2266, 2019.