

DSP BASED FIELD ORIENTED CONTROL OF INDUCTION MOTOR

**A PROJECT
REPORT PHASE II**

Submitted by

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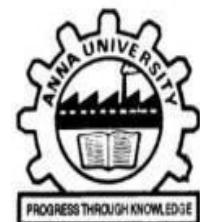
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BONAFIDE CERTIFICATE

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ABSTRACT

Field-oriented control (FOC) is a sophisticated technique for achieving high-precision torque and flux control in induction motors, offering performance comparable to DC machines. This project involved the design and implementation of a sensorless FOC system for a 0.25 HP induction motor using a Texas Instruments C2000 microcontroller and a Fairchild Intelligent Power Module. Both simulation and hardware implementation were conducted. MATLAB/Simulink was employed to model the FOC system, demonstrating significant improvements in dynamic response, including a reduction in settling time by approximately 80% and a decrease in peak overshoot by 90% compared to conventional scalar V/f control. The FOC algorithm was implemented on the C2000 microcontroller, utilizing its ePWM module for Space Vector Pulse Width Modulation (SVPWM) generation. The intelligent power module served as the inverter with a built-in gate driver, while current measurement and feedback were achieved using shunt resistors and differential amplifiers. Motor parameters were accurately measured and estimated using specialized equipment for precise control. The implemented system successfully achieved a load angle of 80-87 degrees, maximizing motor torque across the entire speed range, from zero to rated speed. This project effectively demonstrates the superior performance of FOC compared to scalar control.

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TABLE OF CONTENTS

CHAPTER NO.	TITLE	PAGE NO.
ABSTRACT		i
ACKNOWLEDGEMENT		ii
LIST OF FIGURES		vii
LIST OF ABBREVIATIONS		viii
1 INTRODUCTION		1
1.1 GENERAL		1
1.2 LITERATURE SURVEY		3
1.3 SUMMARY OF LITERATURE SURVEY		4
1.4 OBJECTIVES		5
1.5 ORGANIZATION OF THESIS		5
1.6 CHAPTER SUMMARY		6
2 FIELD ORIENTED CONTROL		7
2.1 INTRODUCTION		7
2.2 BLOCK DIAGRAM OF FIELD ORIENTED CONTROL		7
2.3 WORKING OF FOC		10
2.4 CHAPTER SUMMARY		10
3 SIMULATION RESULTS		11
3.1 BLOCK DIAGRAM OF THE SYSTEM		11
3.2 SOFTWARE FLOW CHART		11
3.3 SPEED CONTROL SUBSYSTEM		12

3.4	CURRENT CONTROL SUBSYSTEM	13
3.4.1	Current Measurement	13
3.4.2	Position And Speed Estimation	14
3.4.3	Control System	15
3.5	SIMULATION RESULTS	16
3.5.1	Load Angle	16
3.5.2	Speed Response	18
3.5.3	Current Response	18
3.6	CHAPTER SUMMARY	20
3.7	KEY FINDINGS	20
4	HARDWARE RESULTS	22
4.1	INDUCTION MOTOR	22
4.2	F28379D LAUNCHPAD	23
4.3	INTELLIGENT POWER MODULE FSAM20SH60A	24
4.4	PCB DESIGN FOR FSAM20SH60A	26
4.5	CURRENT MEASUREMENT	28
4.6	ACIM PARAMETER ESTIMATION	29
4.6.1	Cold Test	30
4.6.2	No-load Test	30
4.6.3	Blocked Rotor Test	32
4.7	SPACE VECTOR PULSE WIDTH MODULATION	33
4.7.1	Generation Of Space Vector PWM With C2000 Microcontroller	34
4.7.2	PWM Frequency Calculation	35
4.8	PWM FREQUENCY (F_{PWM})	35
4.9	TIME BASE CLOCK (T_{TBCLK})	36
4.10	TIMER PERIOD (T_{BPRD})	36
4.10.1	Output Of SVPWM With Low Pass Filter	37

4.10.2	Dead Band	37
4.11	HARDWARE SETUP FOR MOTOR CONTROL	39
4.11.1	DC BUS	39
4.11.2	INVERTER and Controller	39
5	CONCLUSION	43
5.1	GENERAL	43
5.2	SCOPE FOR FUTURE WORK	44

List of Figures

2.1	Block Diagram Of FOC For I.M.	8
3.1	Block Diagram of the System	11
3.2	Software Flow Chart	12
3.3	Speed Control System	13
3.4	Current Measurement	13
3.5	Position and Speed Estimation	14
3.6	Current Control System	15
3.7	Load Angle between Rotor Flux and Stator Flux	16
3.8	Simulink Model for Load Angle Calculation	17
3.9	Speed Response	18
3.10	Ia and Ib Feedback/Measured Currents	19
3.11	Iq Reference and Feedback Currents (Torque producing current)	19
3.12	Id Reference and Feedback Currents (Magnetizing current)	20
4.1	Image of Induction Motor	22
4.2	Image of F28379D Launchpad	24
4.3	Image of FSAM20SH60A module	25
4.4	Application Circuit from FSAM20SH60A Datasheet	27
4.5	PCB Layout Design in Ultiboard	27
4.6	3D View of PCB Layout Design in Ultiboard	28
4.7	Current Sensing Circuit in Multisim	29
4.8	No-load test setup	30
4.9	Fluke 434 power analyzer	30
4.10	No-load equivalent circuit	31
4.11	Blocked rotor equivalent circuit	32
4.12	ePWM block in Simulink	37
4.13	ePWM configuration in Simulink	38

4.14	Hardware setup with RC filter and Launchpad	38
4.15	Output of SVPWM with low pass filter	39
4.16	Dead band time	40
4.17	DC Bus Setup	40
4.18	Inverter and Controller Setup	41
4.19	Complete Hardware Setup	42

LIST OF ABBREVIATIONS

FOC	- Field Oriented Control
AC	- Alternating Current
IM	- Induction Motor
DC	- Direct Current
PWM	- Pulse Width Modulation
PI	- Proportional Integral
PID	- Proportional Integral Derivative
PMSM	- Permanent Magnet Synchronous Motor
SVPWM	- Space Vector Pulse Width Modulation
DSP	- Digital Signal Processor
d-q	- direct-quadrature
VVVF	- Variable Voltage Variable Frequency
ACIM	- AC Induction Motor

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The induction motor, a critical component in industry, has long been a focus of study and innovation due to its robustness, simplicity, and cost-effectiveness. It is a workhorse in various applications, ranging from small appliances to large industrial machines. However, the quest for achieving precise control over its operation has led to the development of sophisticated control strategies, one of which is Field Oriented Control (FOC). This project paper aims to explore the intricacies of FOC, its advantages over traditional control methods such as scalar control, and the practical implementation of its simulation for real-world applications.

Comparisons will also be done between different methods to estimate the rotor flux angle, which is a key parameter for FOC. Trade-offs will be evaluated between using sensorless techniques or physical sensors, such as encoders or hall-effect sensors. It's observed that FOC is more adaptive to the non-linearity and uncertainties of the induction motor, such as parameter variations, and saturation effects.

In industrial applications, where efficiency, performance, and precision control are non-negotiable, the traditional scalar control methods often fall short. Scalar control strategies, such as Volt/Hertz control, are simpler and less costly but do not adequately address the dynamic response and torque control requirements of modern applications. They fail to decouple the flux and torque-producing components of the motor currents, leading to sluggish response and compromised performance under varying loads.

In contrast, Field Oriented Control (FOC) provides a solution to these limitations by treating the induction motor akin to a separately excited DC motor, where torque and flux can be controlled independently. This decoupling allows for precise and independent control of speed and torque, akin to DC motors, which is vital in applications demanding high

dynamic performance such as electric vehicles, CNC machines, and robotics.

The basic principle of FOC is to transform the three-phase stator currents and voltages into a two-phase coordinate system (d-q) that rotates synchronously with the rotor flux. This transformation simplifies the analysis and control of the induction motor, since the d-axis component of the current is responsible for the flux generation, and the q-axis component is responsible for the torque generation. By controlling these two components separately, the FOC can achieve a fast and accurate response to the speed and torque commands.

Significance of FOC in Induction Motors:

- **Decoupling of Torque and Flux:** FOC allows independent control of the magnetic flux and torque components, similar to how DC motors are controlled. This decoupling enhances the dynamic response of the motor and allows for precise speed and position control, which is crucial in applications like robotics and electric vehicles.
- **Improved Efficiency:** By optimizing the control of current flow within the motor, FOC improves the efficiency of the motor. This is particularly beneficial in reducing energy consumption in high-performance applications.
- **Reduced Motor Stress:** Smooth control over torque also means less mechanical stress on the motor components, leading to improved reliability and longer motor life.
- **Dynamic Performance:** The ability to dynamically adjust the motor's performance parameters allows for better adaptation to varying load requirements, which is essential in many industrial applications.

Key components and concepts of the FOC methodology include:

1. Coordinate Transformation: The transformation of the three-phase stator current variables into a two-coordinate (d-q) system using Clarke and Park transformations.

This d-q reference frame rotates synchronously with the rotor flux, simplifying the dynamic model of the induction motor into a form that can be directly controlled.

2. Flux Estimation: The accurate estimation or measurement of the rotor flux position, which is central to the performance of FOC. Sensorless methods can use motor voltage and current to estimate the position, while sensor-based methods use encoders or resolvers for direct measurement.
3. Control Algorithm: A control algorithm that takes the reference speed or torque and calculates the required voltage vectors in the d-q frame, which are then transformed back into three-phase voltages to be applied to the motor.
4. Inverters and PWM: The use of voltage-source inverters and Pulse Width Modulation (PWM) techniques to generate the required voltages and currents that drive the motor according to the FOC strategy.
5. At this moment we've performed the simulation for VVVF and FOC, and obtained the dynamic response of their speed and we've also simulated 180° mode inverter whose calculation is provided. Simulation and experimental results of our project, and discuss the challenges and future work will be presented.

1.2 LITERATURE SURVEY

Arun Dominic Dn et.al (2014) - Analysis of field-oriented controlled induction motor drives overview of sensorless scheme This article explores use of blanking periods and space vector modulation to enhance low-speed drive performance, providing a thorough technique review.[1]

Chen, Wen Zhuo, et al. (2014) - Simulation of Permanent Magnet Synchronous Motor Field oriented Vector Control System The text describes coordinate conversion's role in managing motor currents, especially excitation and torque. Simulation results validate the

vector control method's accuracy, supporting real-world system design.[3]

Dianguo Xu et.al (2018) - A Review of Sensorless Control Methods for AC Motor Drives Sensorless control - signal injection methods are simpler and easier to execute than model reference adaptive system and Kalman filter. Requires large amount of data.[5]

E.S.Tez (1995) A Simple Understanding of Field Orientation For Ac Motor Control The article teaches field-orientation for AC motor control, which aligns the stator and rotor fields for fast torque control. It corrects some wrong ideas about motor models and parameters, and shows a new field-orientation design called INVECTER.[4]

F. Yusivar, N. Hidayat et al (1980) - Implementation of Field Oriented Control for Permanent Magnet Synchronous Motor The article shows how microprocessors can control AC machines better with field orientation, which improves their dynamic performance. It explains the induction motor model and talks about the future possibilities in the field. [2]

1.3 SUMMARY OF LITERATURE SURVEY

Field-oriented control is a technique in AC motor drives that align the stator and rotor magnetic fields for efficient and responsive torque control, introducing advanced control strategies such as INVECTER, which correct misconceptions and improve upon traditional motor models.

The application of coordinate transformation, specifically in Permanent Magnet Synchronous Motors (PMSM), is critical for managing motor currents and optimizing control through Proportional-Integral (PI) controllers and Space Vector Pulse Width Modulation (SVPWM), with simulation results confirming the precision and effectiveness of these vector control methods.

Sensorless control methodologies for AC motor drives, including signal injection, offer a more straightforward and practical approach compared to complex systems like Model Reference Adaptive Systems (MRAS) and Kalman filters, though they require significant data processing.

Integration of microprocessors in the implementation of field-oriented control has significantly enhanced the dynamic performance of AC motors, with Permanent Magnet Synchronous Motors (PMSM) benefiting from improved control theories and practical implementation insights, along with foresight into future advancements in AC motor control.

Sophisticated techniques in field-oriented control of induction motors, such as the use of blanking periods and space vector modulation, are instrumental in improving low-speed drive performance, necessitating an in-depth analysis of these sensorless schemes to further refine control strategies.

1.4 OBJECTIVES

- To simulate field oriented control of an induction motor using MATLAB/Simulink and analyze its performance compared to conventional scalar control.
- To implement different control strategies like proportional, PI and PID control for the current control loop and evaluate their impact on the dynamic response of the motor.
- To propose techniques to improve the low speed performance and dynamic response of the induction motor drive.

1.5 ORGANIZATION OF THESIS

This thesis is organized into four chapters, which are described as follows.

Chapter 1: Deals with the introduction, literature survey, and objectives.

Chapter 2: Explains the functional block diagram and gives an explanation for each block.

Chapter 3: Describes the software and closed-loop operation of the system.

Chapter 4: Describes hardware implementation details of vector controlled induction motor.

Chapter 5: Presents the conclusion, results, and scope for future work.

1.6 CHAPTER SUMMARY

Introduction, literature survey, objectives and organization of thesis are presented in this chapter.

CHAPTER 2

FIELD ORIENTED CONTROL

2.1 INTRODUCTION

The FOC control loop shown involves some key mathematical transformations like the Clarke and Park transforms. The 3-phase stator currents are transformed to a 2-phase orthogonal reference frame by the Clarke transform. The Park transform then rotates this into the synchronous rotational reference frame aligned with the rotor flux. The required rotor position is obtained using incremental encoders, Hall-effect sensors, or sensorless methods. The flux and torque components in this rotating reference frame are decoupled, allowing for separate control through the PI controllers. The outputs of the PI controllers are transformed back to 3-phase voltages to drive the inverter. Space vector PWM is typically used to generate the gate signals for the inverter.

2.2 BLOCK DIAGRAM OF FIELD ORIENTED CONTROL

The Field Oriented Control (FOC) block diagram depicts the implementation of vector control of an AC induction motor (ACIM) using MATLAB. The desired speed (ω_{ref}) is fed into a Proportional-Integral (PI) speed controller to compute the torque reference (T_{ref}). This torque reference, in conjunction with the ACIM control reference, is used to determine the reference direct and quadrature axis currents ($I_{sd_{\text{ref}}}$ and $I_{sq_{\text{ref}}}$), managed by two separate PI controllers for current regulation. The Park transform takes actual motor currents (I_a , I_b) and transforms them using the rotor's electrical position (θ_e), obtained from a position generator along with a sine-cosine lookup. The Inverse Park transform takes the PI controllers' output ($V_{sd_{\text{ref}}}$ and $V_{sq_{\text{ref}}}$) and converts them back to the stationary reference frame (V_α , V_β). Subsequently, these voltages are fed to a space vector generator that produces pulse-width modulation (PWM) signals for the inverter, which then drives the induction motor. The motor's actual speed (ω_r) is measured and compared to the refer-

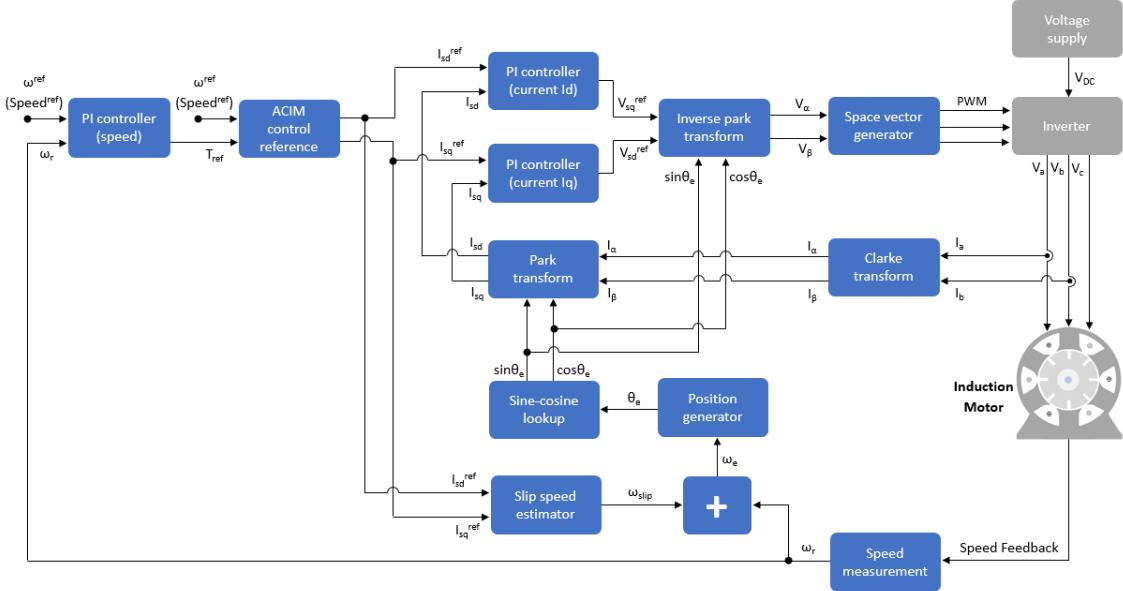


Figure 2.1: Block Diagram Of FOC For I.M.

ence speed to ensure closed-loop control. Additionally, the slip speed estimator feeds into the position generator for accurate control, completing the FOC system loop. The block diagram shown in Fig. 2.1 depicts the main components of FOC for induction motor drive.

This block diagram represents a typical vector control (also known as field-oriented control) for an AC Induction Motor (ACIM). It's an advanced control strategy used in variable frequency drives (VFDs) to control the torque and speed of a three-phase AC induction motor. Let's discuss each block and their roles in the control scheme:

1. PI Controller (speed): This is a Proportional-Integral controller for the speed loop. It takes the speed reference (ω_{ref} or $Speed^{ref}$) and compares it with the actual rotor speed (ω_r). The output of the PI controller is a reference torque (T_{ref}), which sets the desired motor torque corresponding to the target speed.
2. ACIM Control Reference: It translates the reference torque into current components that will achieve this torque. These current components are referenced in the d-q coordinate system, where I_{sd}^{ref} is the direct-axis current reference, and I_{sq}^{ref} is the quadrature-axis current reference.

3. PI Controllers (current I_d and I_q): There are two PI controllers here for the current loop—one for the direct-axis current (I_{sd}) and another for the quadrature-axis current (I_{sq}). These controllers ensure that actual motor currents match the current references derived from the speed controller.
4. Park Transform: This block transforms the three-phase stator currents (I_a , I_b , I_c) into a two-axis current vector (I_d , I_q) in the rotating reference frame (d-q frame), which simplifies control of the motor.
5. Slip Speed Estimator: It estimates the slip speed (ω_{slip}) of the motor, which is the difference between the synchronous speed and the actual rotor speed. This is used, along with the rotor speed, to compute the electrical angle.
6. Inverse Park Transform: This block takes the current references in the d-q axis (V_{sd}^{ref} , V_{sq}^{ref}) and converts them into voltage references in the stationary reference frame (V_α , V_β) required for generating PWM signals.
7. Space Vector Generator: This module generates the PWM (Pulse Width Modulation) signals necessary to control switches in the inverter, based on the stationary reference frame voltages.
8. Inverter: The inverter takes the DC voltage supply (V_{dc}) and switches it to synthesize variable-frequency AC voltage for the motor using the PWM signals it receives. This results in three-phase output voltages (V_a , V_b , V_c) that control the motor.
9. Induction Motor: The actual physical motor that converts electrical power into mechanical power, which is controlled by the variable input voltages.
10. Speed Feedback: The rotor speed is measured and fed back into the control system to adjust the control signal and maintain the desired speed accurately.

2.3 WORKING OF FOC

The main components and their working is as follows:

1. Three phase voltages and currents from the motor are converted to two phase stationary reference frame using Clarke transformation.
2. The stationary reference frame is then converted to synchronous rotating reference frame aligned with the rotor flux using Park transformation.
3. Using feedback of rotor position/speed, flux and torque controllers generate reference current components in rotating frame.
4. Inverse Park and Clarke transforms convert these reference currents to three phase currents for the voltage source inverter.
5. SVPWM scheme is used to generate switching pulses for the inverter to achieve the reference currents.
6. Inverter supplies controlled three phase voltages to drive the induction motor.

2.4 CHAPTER SUMMARY

Introduction, block diagram and working of FOC are presented in this chapter.

CHAPTER 3

SIMULATION RESULTS

3.1 BLOCK DIAGRAM OF THE SYSTEM

The block diagram of the Field-Oriented Control (FOC) system for an AC induction motor is shown in Figure 3.1. The system consists of two main subsystems: the Speed Control Subsystem and the Current Control Subsystem. The Speed Control Subsystem is responsible for generating the torque reference values based on the speed reference and feedback values. The Current Control Subsystem is responsible for tracking the reference currents and generating the appropriate voltage references for the inverter to control the motor's currents. The system also includes a Current Measurement block, a Flux Observer block, and a Speed Estimation block to provide the necessary feedback signals for the control system.

The current control system is run on ADC end of conversion interrupt. The system operates at a PWM frequency of 15 kHz.

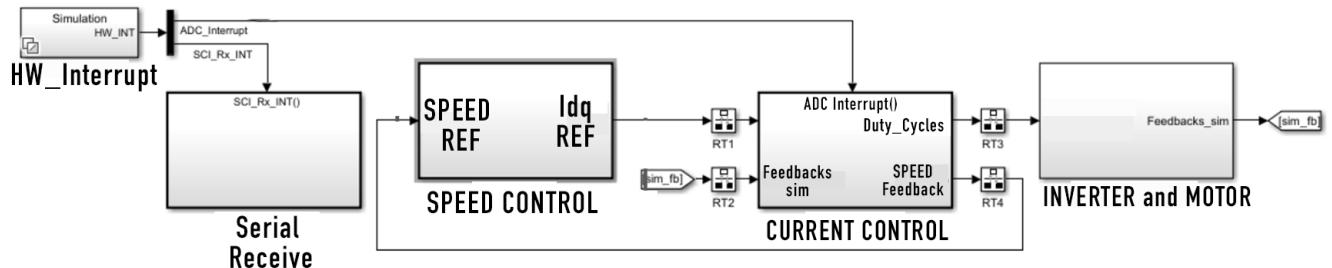


Figure 3.1: Block Diagram of the System

3.2 SOFTWARE FLOW CHART

The software flow chart in Figure 3.2 illustrates the sequence of operations in the FOC control system for an AC induction motor. The flow chart outlines the key steps involved in the control process, including the initialization of the system, the measurement of the

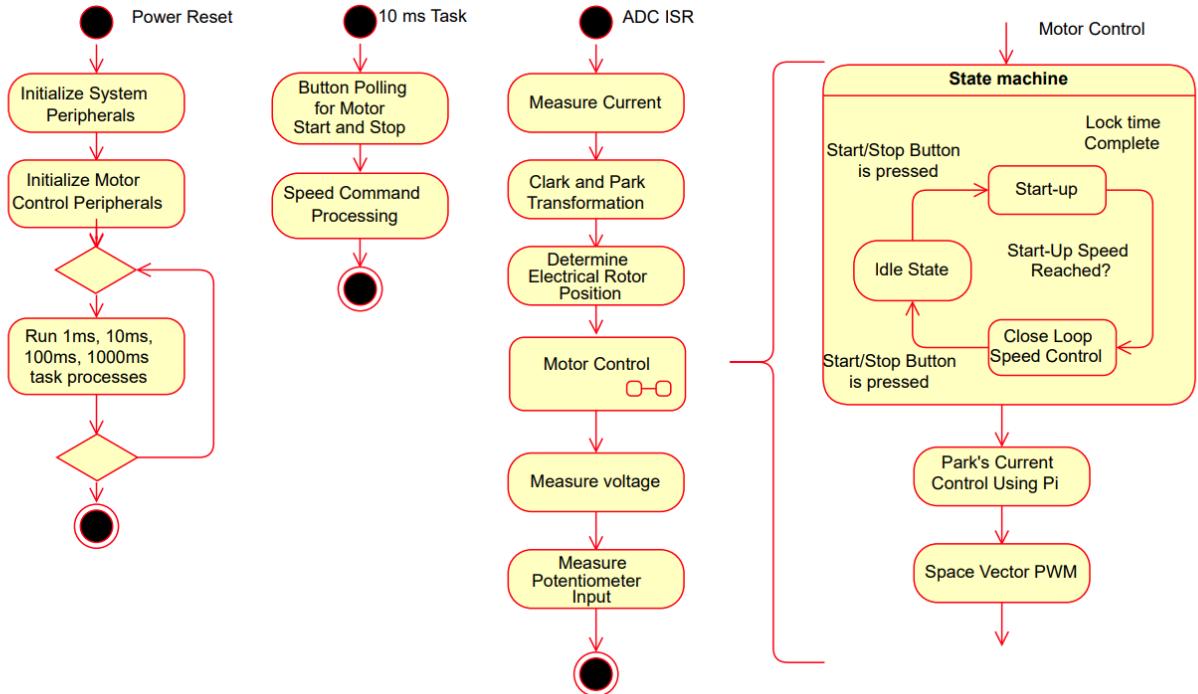


Figure 3.2: Software Flow Chart

motor's currents and voltages, the estimation of the motor's speed and position, and the generation of the appropriate control signals to regulate the motor's speed and torque.

3.3 SPEED CONTROL SUBSYSTEM

The speed control system shown in Figure 3.3 consists of a DataStoreRead block that holds the speed reference value received from the host computer, a Discrete IIR lowpass filter block to cancel the zeros in the system, and a Discrete PID Controller with anti-windup block that takes the speed reference and feedback values as inputs and generates the torque reference as output.

The ACIM Control reference block then takes the torque reference and speed reference as inputs and generates the I_{sdref} and I_{sqref} values, which are the reference values for the current control loop. The DQ limiter block is used to limit the magnitude of the vector represented in the d-q reference frame, with the option to prioritize either the d-axis or q-axis component.

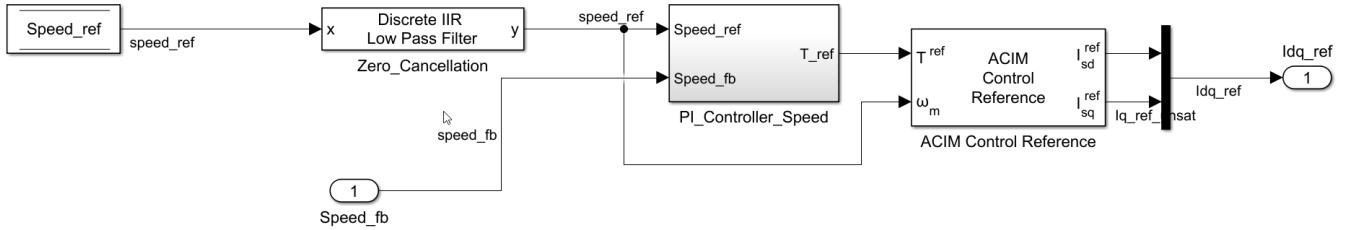


Figure 3.3: Speed Control System

3.4 CURRENT CONTROL SUBSYSTEM

3.4.1 Current Measurement

The current measurement part of the Input Scaling block shown in Figure 3.4

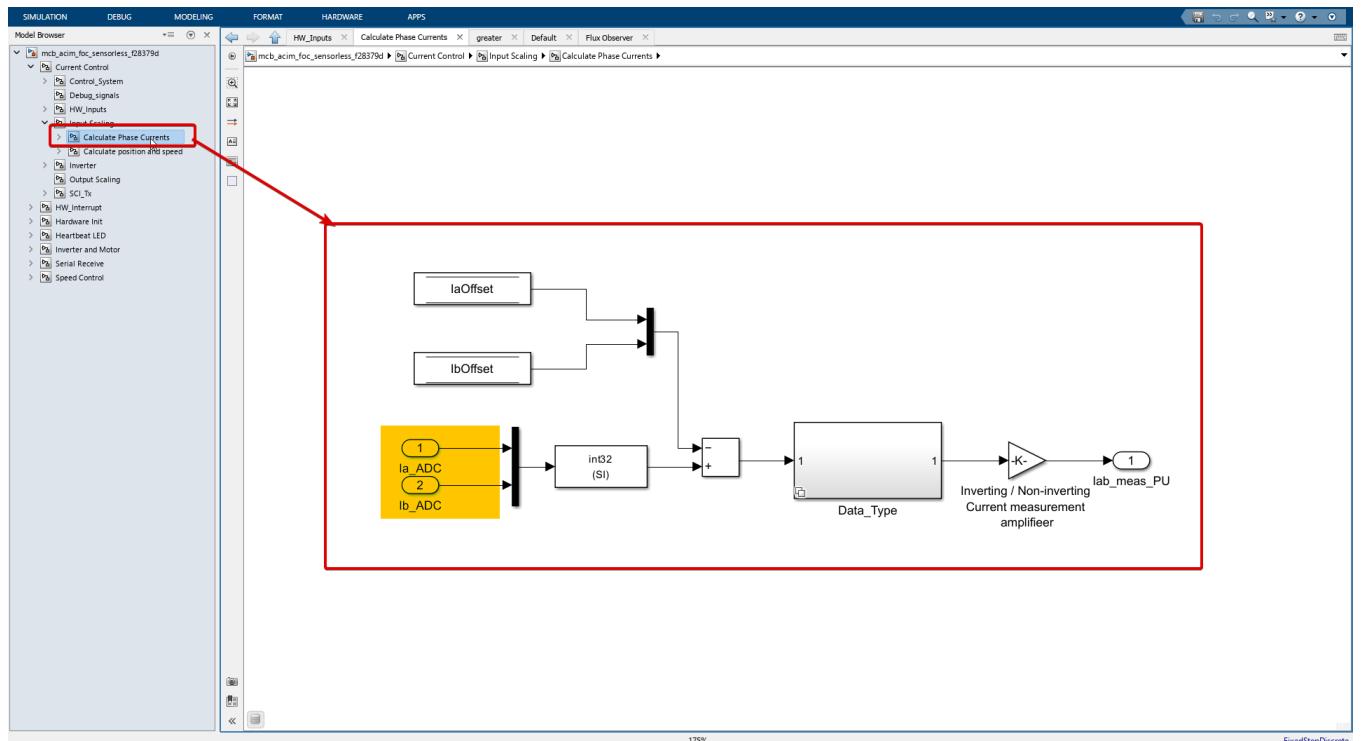


Figure 3.4: Current Measurement

converts the $I_{a,ADC}$ and $I_{b,ADC}$ inputs from the ADCs to the appropriate data type (int32) and removes the offsets ($I_{a,offset}$ and $I_{b,offset}$) that were previously calibrated. The signals then go through a series of gain blocks to convert them to per-unit (PU) values. The first gain block converts the ADC voltage to the actual voltage, the second gain block

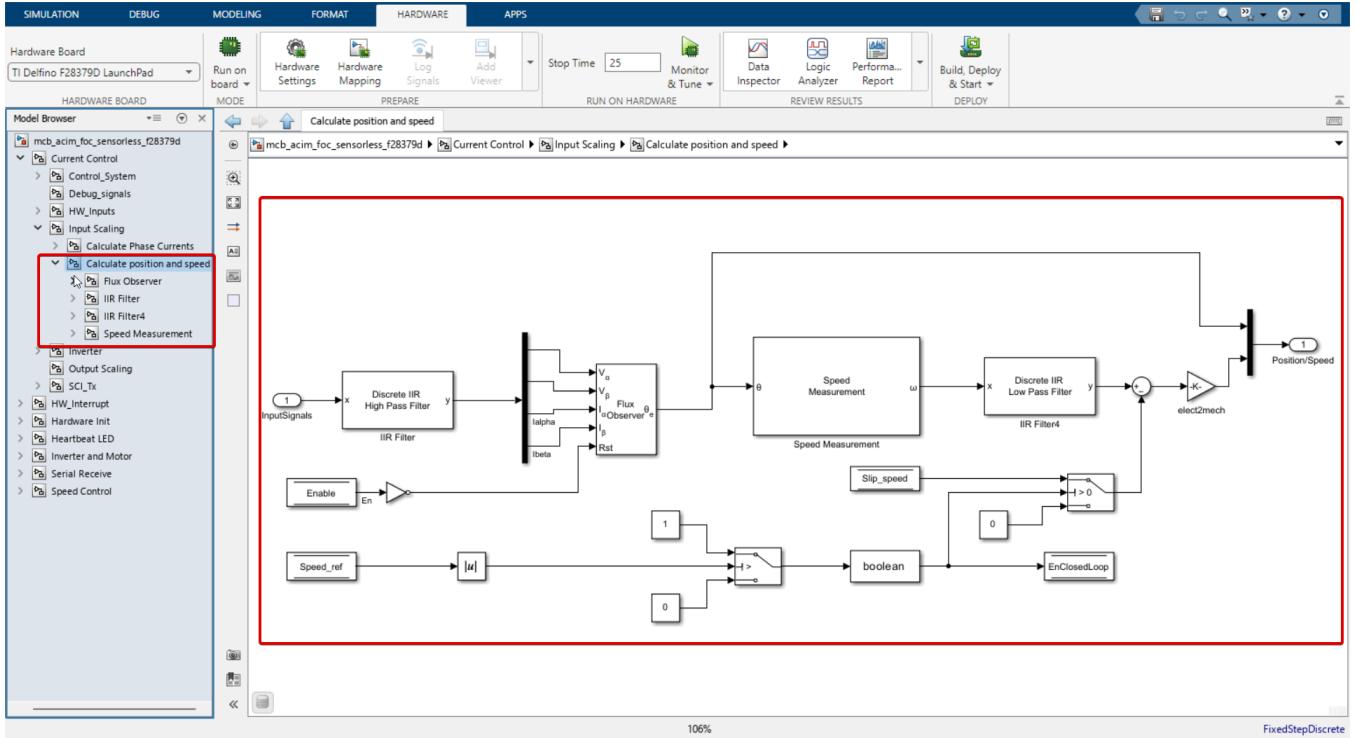


Figure 3.5: Position and Speed Estimation

converts the voltage to current using the inverter's current sense voltage per amp, and the third gain block converts the current to PU using the motor's base current.

3.4.2 Position And Speed Estimation

The position and speed estimation part of the Input Scaling block shown in Figure 3.5 uses the VI_{fb} signal, which contains the motor's voltage and current in the $\alpha\beta$ reference frame. This signal goes through a high-pass filter to remove low-frequency noise. The filtered signals are then fed into the Flux Observer block, which estimates the stator flux position. The estimated stator flux position is then used in the Speed Estimation block to calculate the motor's speed. The estimated speed is filtered using a low-pass IIR filter to remove high-frequency noise. The final rotor speed is calculated by subtracting the slip speed from the estimated stator flux speed and then dividing by the number of pole pairs to get the mechanical speed.

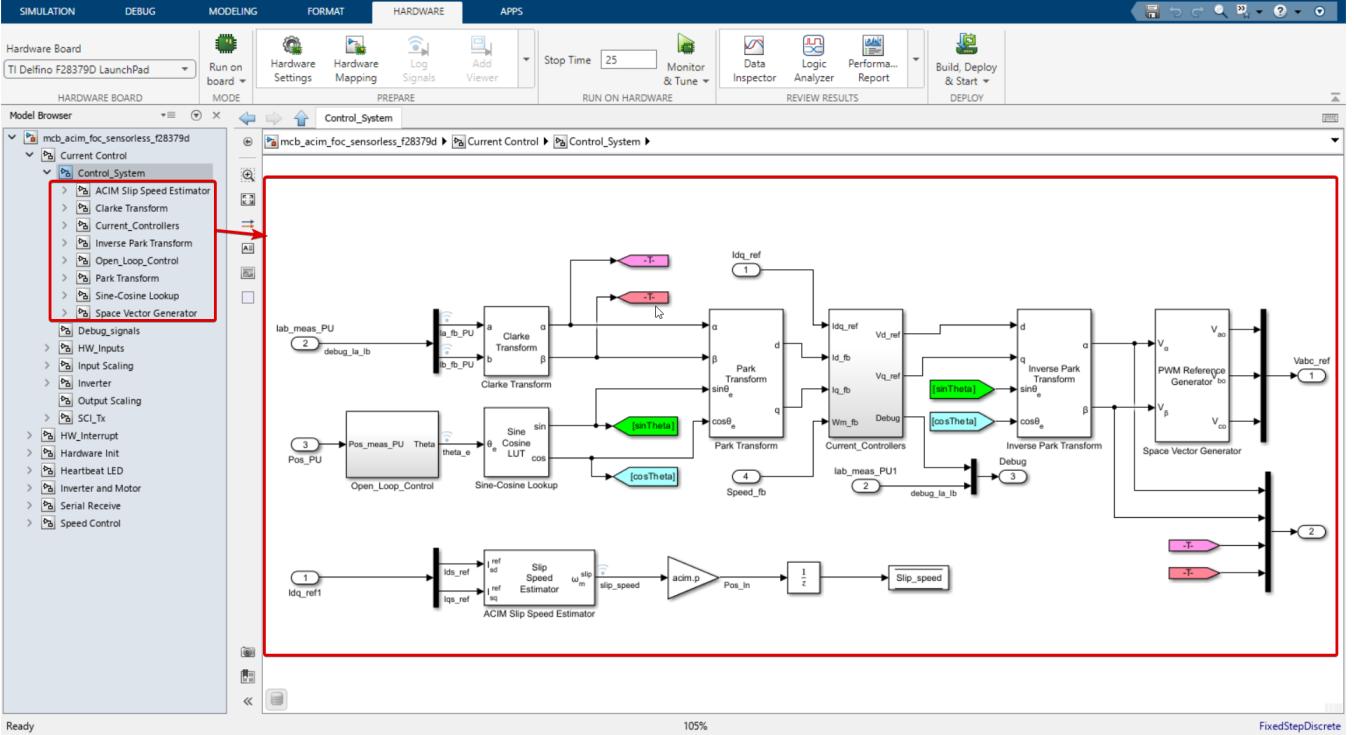


Figure 3.6: Current Control System

3.4.3 Control System

The control system shown in Figure 3.6 implemented in the inner current loop consists of two main components: the current controllers and the DQO transformation.

The current controllers use Proportional-Integral (PI) controllers to minimize the error between the reference currents (I_{dq_ref}) and the feedback currents (I_{d_fb} and I_{q_fb}). The output of the PI controllers is then limited, filtered, and adjusted using a feedforward controller and a saturation function to ensure safe and reliable operation of the system. The adjusted d-axis current is then used to generate the reference voltages (V_{d_ref} and V_{q_ref}) in the DQ frame. These reference voltages are then transformed into the alpha-beta frame using the stator flux position (θ) and fed into the PWM reference generator block, which generates the three-phase voltage references for the inverter. This inner current loop ensures that the actual currents closely follow the desired reference currents, which is crucial for the overall performance and stability of the control system.

3.5 SIMULATION RESULTS

3.5.1 Load Angle

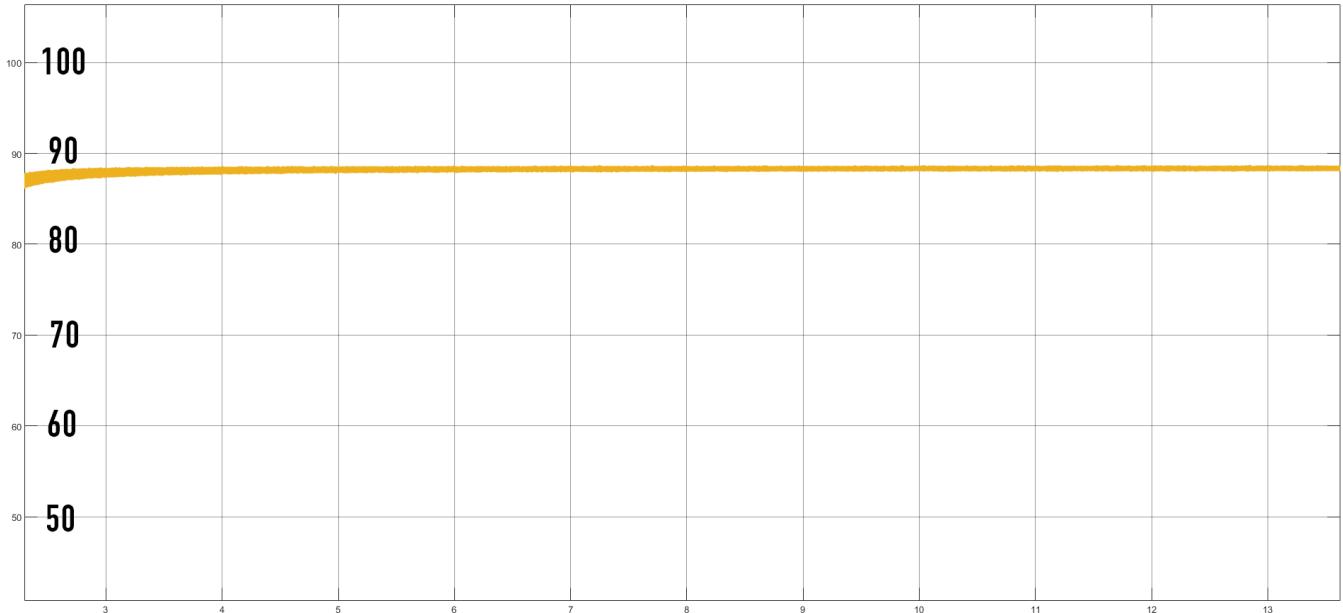


Figure 3.7: Load Angle between Rotor Flux and Stator Flux

Figure 3.7 shows the load angle between the rotor flux and the stator flux. The x-axis indicates time (in seconds), and the y-axis denotes the load angle (in degrees). The waveform illustrates how the load angle changes over time, eventually settling around 90 degrees.

The load angle, also known as the torque angle, is a critical parameter in the vector control of induction machines. It is the angle between the rotor flux vector and the stator current vector in the rotor-flux-oriented reference frame. The load angle is directly related to the electromagnetic torque produced by the motor.

In the ideal case of maximum torque per ampere control strategy, the load angle should be maintained at 90 degrees. This is because the torque produced by the induction machine is directly proportional to the sine of the load angle. Therefore, to maximize the torque output for a given current, the load angle should be maintained at 90 degrees, where the sine function reaches its maximum value.

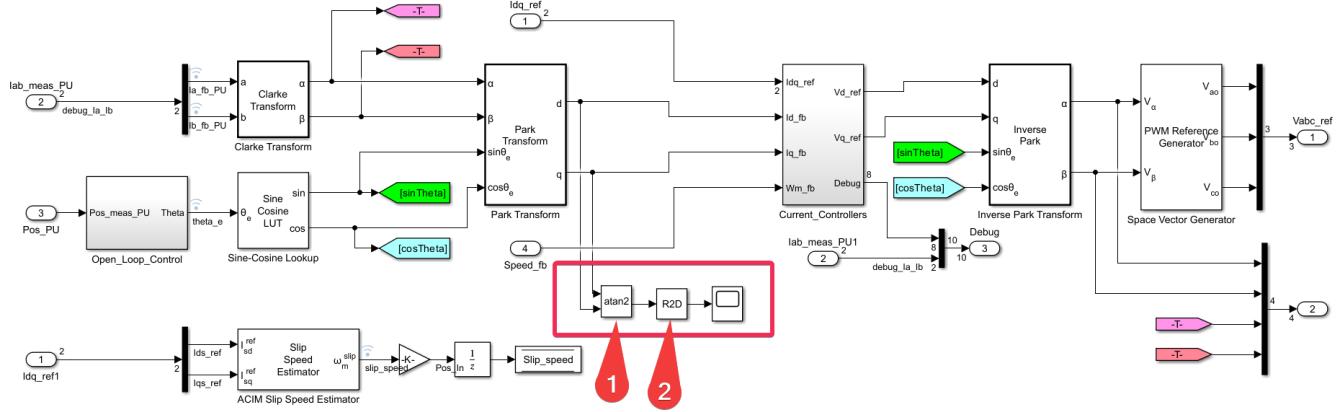


Figure 3.8: Simulink Model for Load Angle Calculation

The settling of the load angle around 90 degrees in the simulation results indicates that the vector control system is effectively controlling the motor to operate at the point of maximum efficiency. This validates the performance of the control system in managing the machine's dynamics and achieving efficient operation.

Figure 3.8 shows the Simulink model and exact blocks used for getting the load angle. The model includes Park transform blocks, which are used to transform the three-phase stator currents into the rotor-flux-oriented reference frame. The transformed *D* and *Q* currents are then input to the ‘Atan2’ block labeled 1 in the figure.

The ‘Atan2’ block, also known as the four-quadrant inverse tangent function, calculates the angle from the *D* and *Q* currents. Unlike the standard inverse tangent function, the ‘Atan2’ function takes two arguments and can return values in all four quadrants, which is necessary for accurately representing the load angle.

The output of the ‘Atan2’ block, which is the load angle in radians, is then converted to degrees using the ‘Radian to Degree’ block labeled 2 in the figure. The final output is displayed on a scope, which shows the load angle over time.

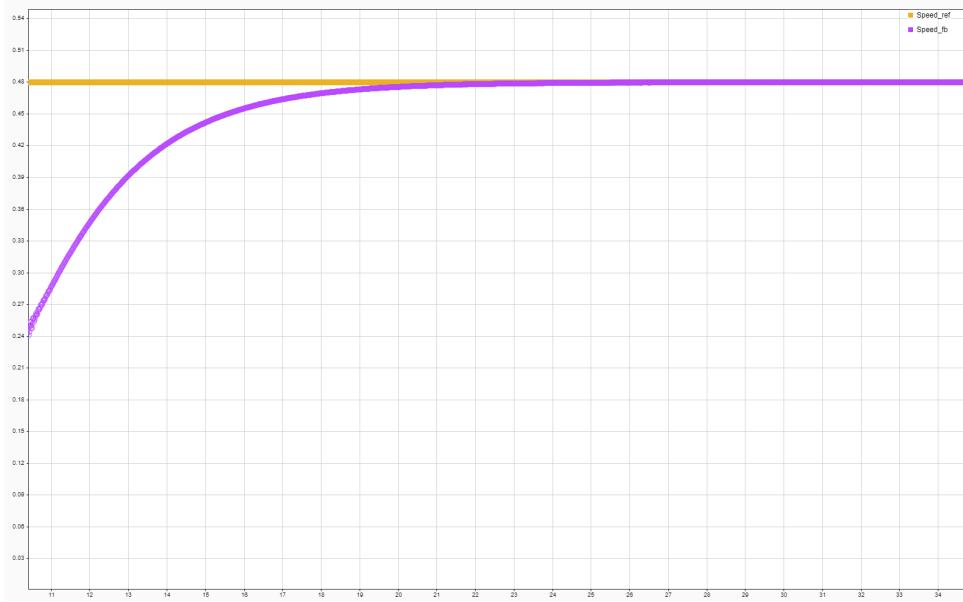


Figure 3.9: Speed Response

3.5.2 Speed Response

Figure 3.9 shows the speed response of the induction machine under vector control. The x-axis represents time (in seconds), and the y-axis represents speed (in RPM). The waveform demonstrates the machine's speed over time. The speed reference is set to 0.5 pu. The speed response shows that the machine's speed closely follows the reference, indicating the effectiveness of the speed control subsystem in managing the motor's speed.

3.5.3 Current Response

Figure 3.10 displays the feedback or measured currents for I_a and I_b . The x-axis signifies time (in seconds), and the y-axis represents current (in per unit).

The figure 3.11 shows the reference and feedback currents for I_q , which is responsible for producing torque. The x-axis signifies time (in seconds), and the y-axis represents current (in per unit). The waveform illustrates how these currents change over time.

The figure 3.12 displays the reference and feedback currents for I_d , which is responsible for magnetizing the motor. The x-axis indicates time (in seconds), and the y-axis

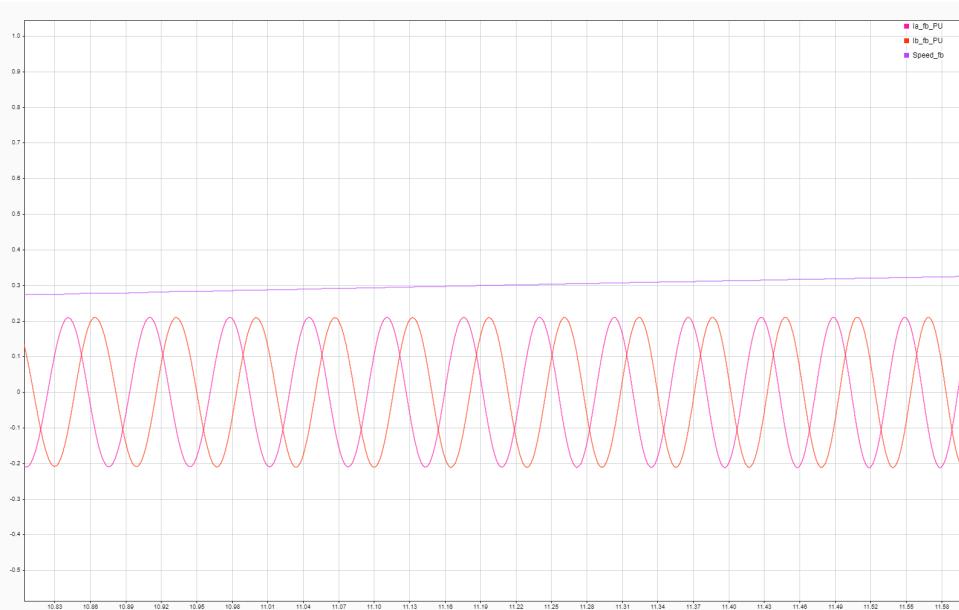


Figure 3.10: I_a and I_b Feedback/Measured Currents

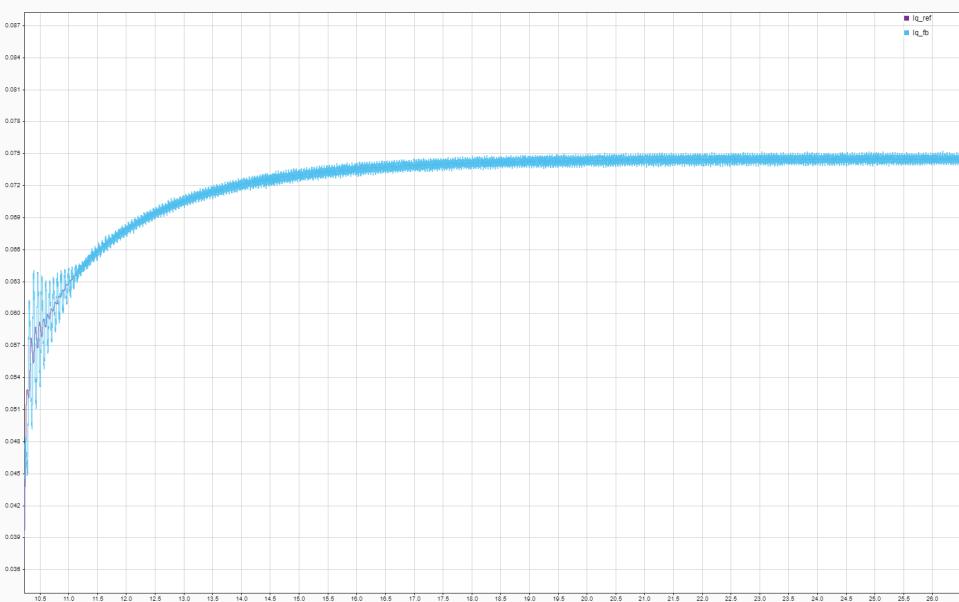


Figure 3.11: I_q Reference and Feedback Currents (Torque producing current)

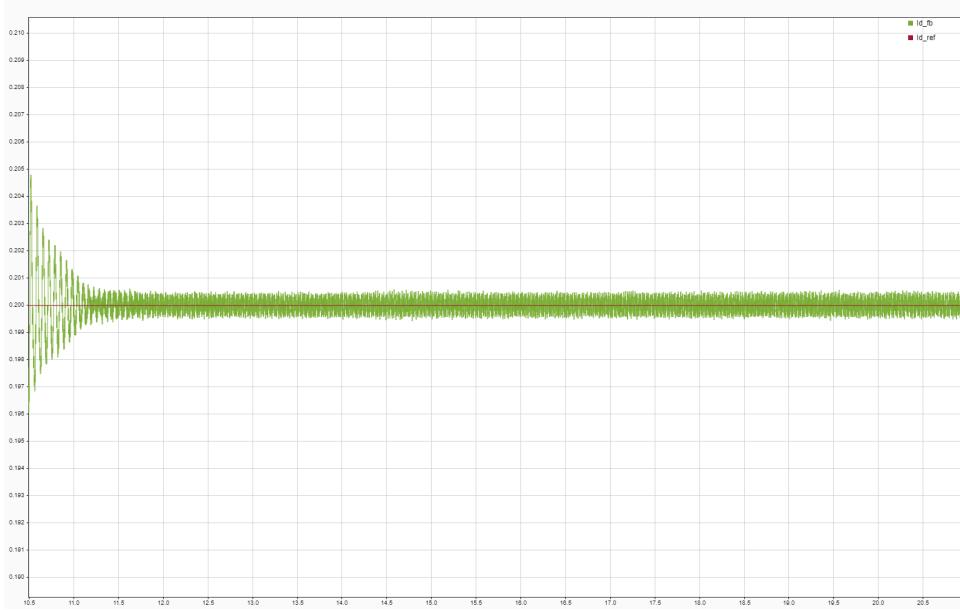


Figure 3.12: Id Reference and Feedback Currents (Magnetizing current)

represents current (in per unit). The waveform illustrates how these currents change over time. The oscillations at the beginning of the simulation are due to the initial transient response of the control system as it tries to stabilize the motor currents.

3.6 CHAPTER SUMMARY

This chapter presented the simulation results FOC control system for an AC induction motor. The simulation was structured to validate various subsystems including speed control, current measurement, position and speed estimation, and the overall control system. Each section provided detailed insights through block diagrams and response graphs to illustrate the system's performance under simulated conditions.

3.7 KEY FINDINGS

- The **Speed Control Subsystem** effectively managed the motor's speed by adjusting the torque reference values, ensuring that the motor speed follows the set reference closely.

- The **Current Control Subsystem** demonstrated robust performance in tracking the reference currents accurately, which is crucial for the stability and efficiency of the motor operation.
- **Position and Speed Estimation** techniques were validated to show precise estimation of the motor's speed and position, which are critical for the effective vector control of the AC induction motor.
- The overall system showed a **high degree of accuracy and responsiveness** in the speed and current responses, validating the effectiveness of the designed control strategies in managing the dynamics of the AC induction motor.

In conclusion, this chapter has laid a solid foundation for the practical implementation of the control system, with simulation results strongly supporting the theoretical designs.

CHAPTER 4

HARDWARE RESULTS

4.1 INDUCTION MOTOR

Induction motors, also known as asynchronous motors, are widely used in various industrial applications due to their simplicity, durability, and cost-effectiveness. They operate on the principle of electromagnetic induction, wherein a rotating magnetic field in the stator induces a current in the rotor, thus creating torque.

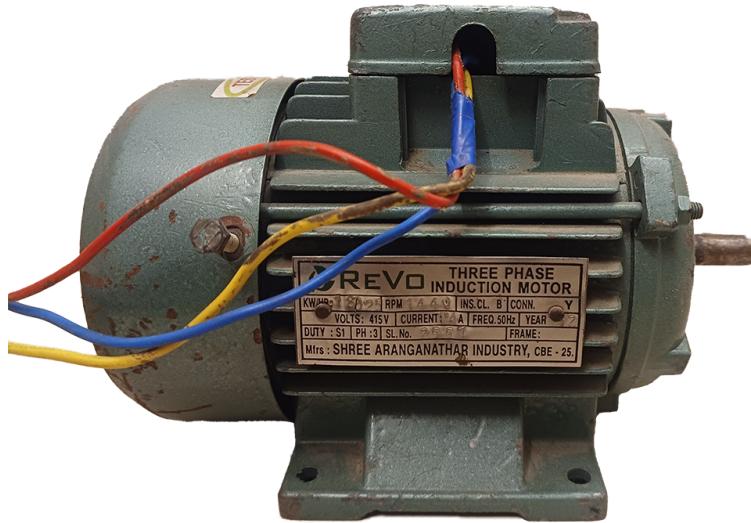


Figure 4.1: Image of Induction Motor

We are utilizing a Revo 3-phase induction motor with the following specifications:

Parameter	Value
Power	0.25 Hp
Voltage	415 V (L-L) RMS
Current	1.4 A
Frequency	50 Hz
Speed	1440 rpm
Phase	3

Table 4.1: Nameplate Details of Induction motor

4.2 F28379D LAUNCHPAD

The F28379D Launchpad, officially known as the LAUNCHXL-F28379D, is a powerful development board from Texas Instruments, designed around the TMS320F28379D microcontroller. This microcontroller is part of the C2000™ Piccolo™ family, renowned for its high-performance processing capabilities, which are particularly suited for engineering applications requiring real-time processing and control.

Core Features:

- **Processor:** The TMS320F28379D microcontroller features a dual-core configuration with a C28x CPU and a secondary CLA (Control Law Accelerator) CPU, enhancing its ability to handle complex control algorithms.
- **Memory:** It includes onboard flash memory and RAM, facilitating robust applications and advanced computation.
- **Connectivity:** Provides extensive connectivity options including CAN, USB, and Ethernet, supporting a wide range of communication protocols.
- **Analog and Digital I/O:** Equipped with multiple ADC (Analog-to-Digital Converter) channels, DAC (Digital-to-Analog Converter) outputs, and PWM (Pulse Width Modulation) outputs for comprehensive sensor integration and actuator control.

Applications: The F28379D Launchpad is particularly adept at handling applications that require real-time processing capabilities such as motor control, renewable energy systems, power supplies, and advanced sensing systems. Its high-speed processing and diverse I/O options make it ideal for both academic research and industrial applications.

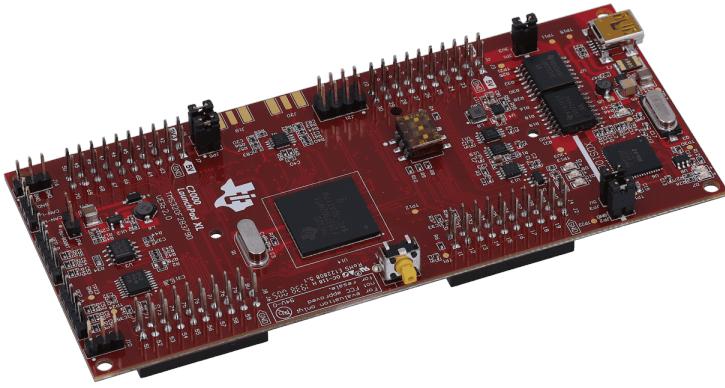


Figure 4.2: Image of F28379D Launchpad

The integration of the F28379D Launchpad in projects offers a robust platform for developing sophisticated control systems and algorithms, facilitating innovation and efficiency in system design and implementation.

4.3 INTELLIGENT POWER MODULE FSAM20SH60A

We integrated the FSAM20SH60A, a Motion SPM® 2 module, as a fundamental component. This device is UL Certified (No. E209204 UL1557) and serves as a high-performance 3-phase IGBT inverter with integrated gate drivers and protection, making it an ideal solution for AC Induction, BLDC, and PMSM motors.

Key Features:

- **Efficiency and Safety:** Designed with low-loss, short-circuit rated IGBTs and an optimized gate drive to minimize electromagnetic interference (EMI) and losses. It incorporates multiple on-module protection features such as under-voltage lockouts, over-current shutdown, thermal monitoring, and fault reporting, ensuring robust and reliable operation.
- **Thermal Management:** Features low thermal resistance through the use of a ceramic substrate. It also includes separate open-emitter pins from low-side IGBTs for three-phase current sensing, supporting a wide variety of control algorithms.

- **Performance Specifications:** Tailored for a 15 kHz switching frequency with a built-in NTC thermistor for accurate temperature monitoring. It operates on a single-grounded power supply and offers an inverter power rating of 1.5 kW at an input voltage range of 100–253 VAC.
- **Customization and Isolation:** Provides an adjustable current protection level, allowing for customization via the selection of Sense-IGBT Emitter's external R_s . Boasts an impressive isolation rating of 2500 Vrms per minute.
- **High-Voltage Integrated Circuit:** The high-speed HVIC integrated into the FSAM20SH60A requires only a single supply voltage and effectively translates the incoming logic-level gate inputs to the high-voltage, high-current drive signals required to properly drive the module's internal IGBTs.



Figure 1. Package Overview

Figure 4.3: Image of FSAM20SH60A module

This integration of the FSAM20SH60A enhances our project by providing a compact, efficient, and reliable solution for motor control applications, supporting our objectives of achieving high performance and durability in our designs.

4.4 PCB DESIGN FOR FSAM20SH60A

In the PCB design section of our project, we developed a printed circuit board for the FSAM20SH60A, an intelligent power module. Our design approach was heavily influenced by the application circuit provided in the module's datasheet.

Design Considerations:

- **Reference Design:** The application circuit from the datasheet served as a crucial reference, ensuring adherence to the technical specifications and requirements of the FSAM20SH60A.
- **Component Placement and Trace Routing:** Special attention was given to the layout and routing of circuit traces and the strategic placement of components, focusing particularly on effective thermal management.
- **Functional Integration:** The design accommodates features such as three-phase current sensing and a single-grounded power supply setup. It also supports the functionality of the built-in NTC thermistor for temperature monitoring and the high-speed HVIC.
- **Customization Features:** Provisions were made for adjusting the current protection level through the selection of Sense-IGBT Emitter's external Rs.

Tools Used: Software tools from National Instrument's circuit design suite were utilized. Multisim 14.3 aided in schematic capture, while Ultiboard 14.3 facilitated the PCB layout design.

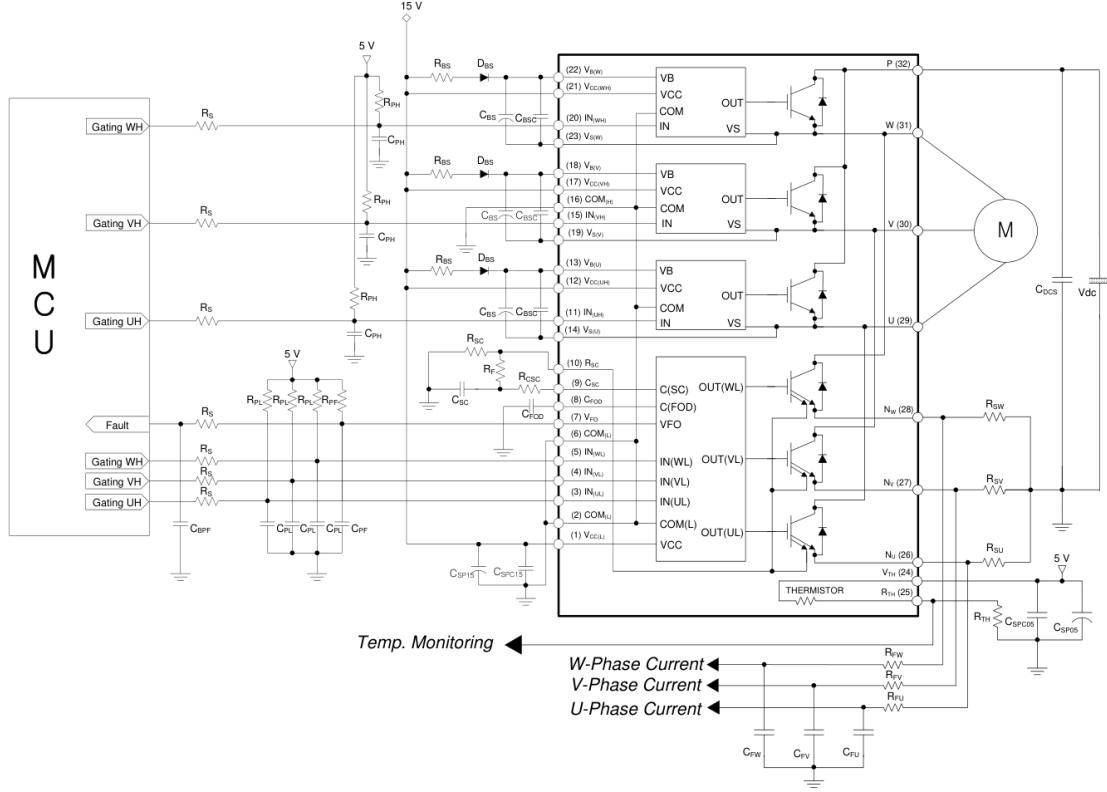


Figure 4.4: Application Circuit from FSAM20SH60A Datasheet

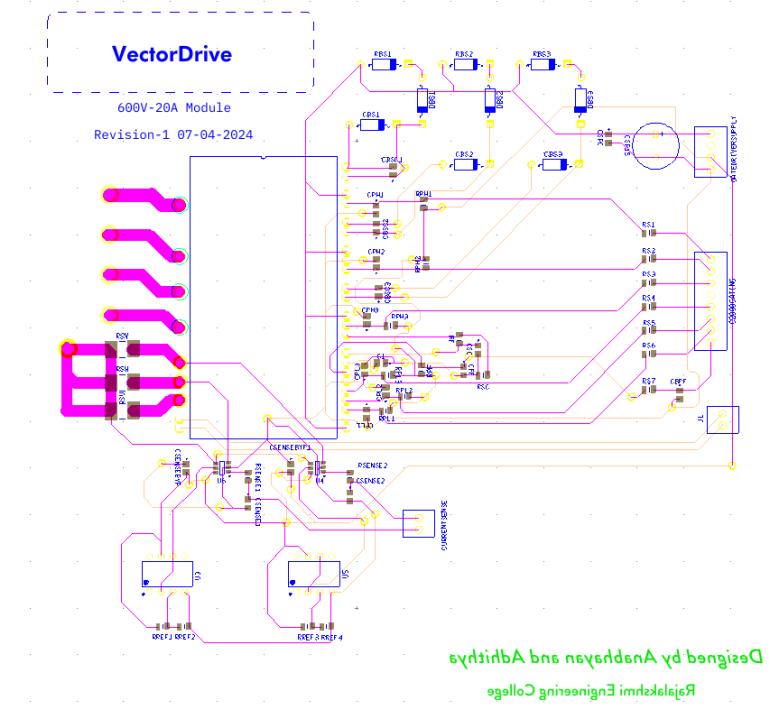


Figure 4.5: PCB Layout Design in Ultiboard

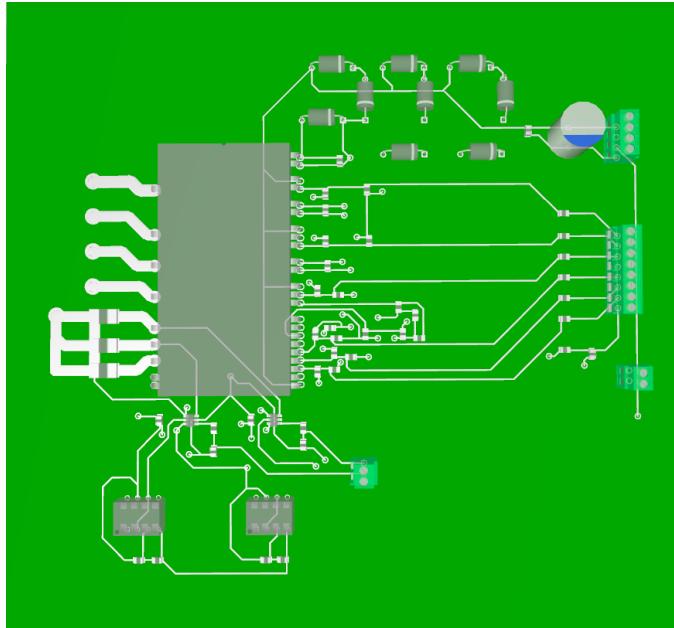


Figure 4.6: 3D View of PCB Layout Design in Ultiboard

This structured approach in the PCB design ensures that the board not only meets the functional requirements of the FSAM20SH60A module but also enhances reliability and performance in practical applications.

4.5 CURRENT MEASUREMENT

In our project, we implemented a strategy for current measurement using a shunt power resistor of 5 milli-ohms. This resistor was incorporated into two of the phase low pass filters, providing a reliable method for detecting and measuring the current flow.

Following the current detection, the signal was then directed to an IA182 operational amplifier. This component was crucial in amplifying the signal to a level suitable for further processing. The IA182 opamp was selected due to its high precision and stability, ensuring accurate amplification of the current signal.

Post amplification, the signal was fed into the Analog-to-Digital Converter (ADC) of the F28379D Launchpad. This conversion process transformed the analog current signal into a digital format, enabling the microcontroller to effectively interpret and utilize the data for further processing and control within the system.

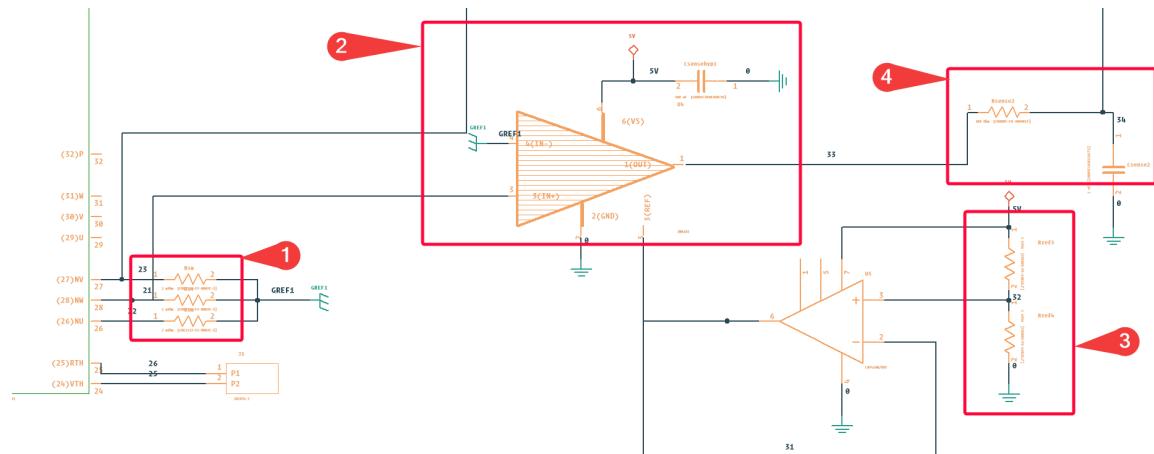


Figure 4.7: Current Sensing Circuit in Multisim

The current sensing circuit, shown in Figure 4.7 , consists of several components that work together to accurately measure current. The circuit utilizes two $5\text{m}\Omega$ current shunt resistors (1) to measure the current, a bidirectional differential current sense amplifier (2) to amplify the sensed current, and a voltage divider comprising two $10\text{k}\Omega$ resistors (3) to level-shift the sense voltage by 2.5V. Additionally, a decoupling capacitor (4) is used to remove high-frequency noise and oppose quick changes in voltage, while a series resistor is used to match the source impedance with the trace impedance, thereby preventing signal attenuation or reflection.

4.6 ACIM PARAMETER ESTIMATION

A Fluke energy analyser is used over regular analog meters for more reliable and accurate measurement of the voltage, current and active power. But, for low current and power measurements properly calibrated analog meters would suffice as the the energy analyser wouldn't be able to measure currents less than one amp.

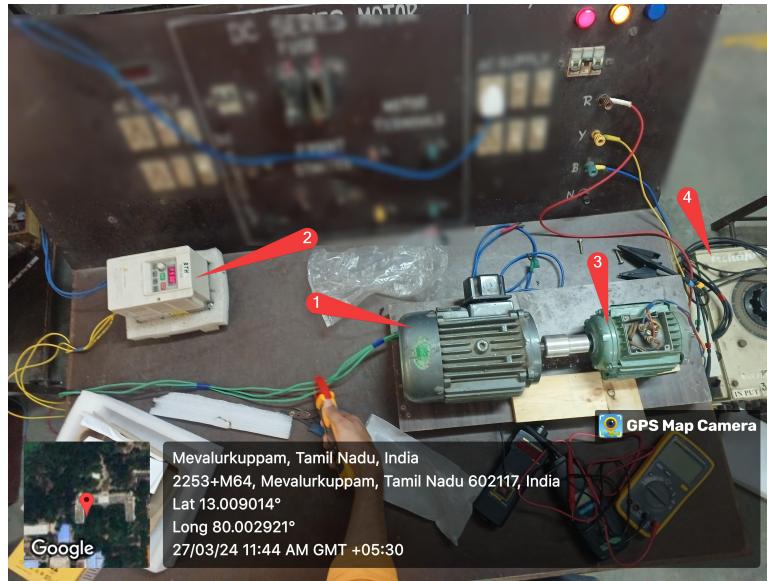


Figure 4.8: No-load test setup



Figure 4.9: Fluke 434 power analyzer

4.6.1 Cold Test

The stator resistance is measured by running the motor at its rated current for 5 minutes or up until it reaches its thermal equilibrium.

4.6.2 No-load Test

The no-load setup has 1Hp induction motor connected to variable frequency drive (VFD) to supply no-load losses like friction and windage losses of 0.25Hp motor which is connected to the power analyzer as shown in 4.9

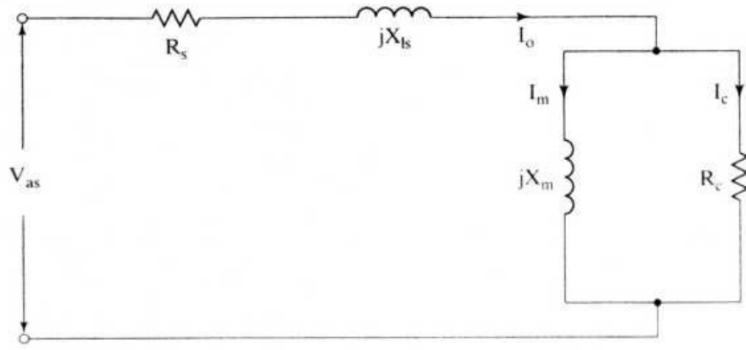


Figure 4.10: No-load equivalent circuit

The no-load power factor is given by:

$$\cos \phi_0 = \frac{P_i}{V_{as} I_0} \quad (1)$$

The magnetizing current is calculated as:

$$I_m = I_0 \sin \phi_0 \quad (2)$$

The core-loss current is given by:

$$I_c = I_0 \cos \phi_0 \quad (3)$$

The magnetizing inductance is computed from:

$$L_m = \frac{V_{as}}{2\pi f_i I_m} \quad (4)$$

The core-loss resistance is given by:

$$R_c = \frac{V_{as}}{I_c} \quad (5)$$

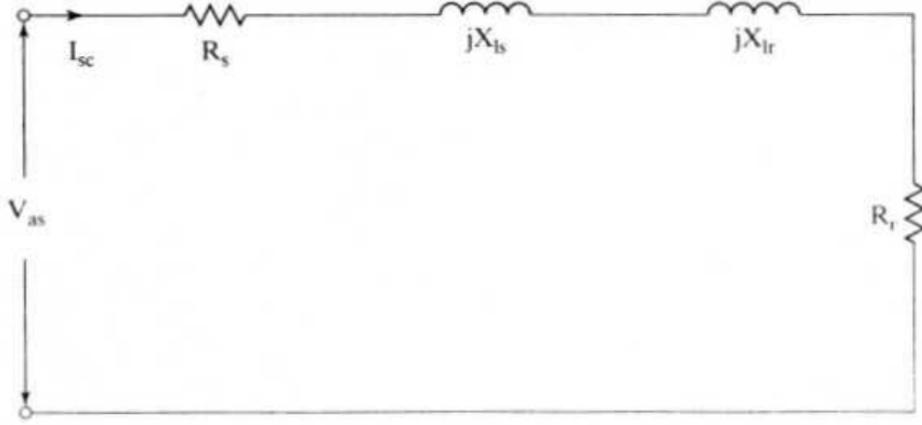


Figure 4.11: Blocked rotor equivalent circuit

4.6.3 Blocked Rotor Test

The short-circuit power factor obtained from the equivalent circuit is:

$$\cos \phi_{sc} = \frac{P_{sc}}{V_{sc} I_{sc}} \quad (6)$$

The short-circuit impedance is given by:

$$Z_{sc} = \frac{V_{sc}}{I_{sc}} \quad (7)$$

From which the rotor resistance and total leakage reactance are computed as:

$$R_r = Z_{sc} \cos \phi_{sc} - R_s \quad (8)$$

$$X_{eq} = Z_{sc} \sin \phi_{sc} \quad (9)$$

where the total leakage reactance per phase, X_{eq} , is the sum of the stator and referred-rotor leakage reactances, given as:

$$X_{eq} = X_{ls} + X_{lr} \quad (10)$$

Based on the above test and calculations, the equivalent circuit parameters are com-

puted as follows:

$$L_m = 1.01 \text{ H}, \quad R_c = 1555.85 \Omega$$

$$R_r = 5.02 \Omega, \quad X_{ls} = 50.47 \Omega, \quad X_{lr} = 50.47 \Omega$$

4.7 SPACE VECTOR PULSE WIDTH MODULATION

Space Vector PWM has several advantages over Sine PWM

- Higher voltage utilization: SVPWM can utilize up to 15% more DC bus voltage compared to SPWM. This means for the same DC supply voltage, an inverter with SVPWM can provide a higher output voltage.
- Better harmonic performance: SVPWM results in lower total harmonic distortion (THD) compared to SPWM. This leads to a better quality of the output voltage and current waveforms, which is particularly important in applications like drives where harmonics can cause heating and torque pulsations.
- Reduced switching losses: SVPWM requires fewer switching operations for the inverter switches compared to SPWM. This results in lower switching losses, leading to higher efficiency and reduced heating of the inverter switches.
- Improved dynamic response: The space vector representation used in SVPWM allows for a more precise control of the output voltage vector, leading to an improved dynamic response. This is particularly beneficial in applications like motor drives where a fast dynamic response is required.
- Vector control capability: SVPWM allows for vector control of the output voltage, which is not possible with SPWM. This enables more complex control strategies,

such as field-oriented control (FOC), which can provide better performance in applications like motor drives.

- Flexibility: SVPWM allows for flexible control of the output voltage magnitude and frequency, as well as the phase relationship between the output voltage and current. This flexibility makes it suitable for a wide range of applications.

4.7.1 Generation Of Space Vector PWM With C2000 Microcontroller

To generate space vector PWM wave for the switches C2000 series microcontroller offers a hardware level module called ePWM or enhanced PWM module. It enables to generate PWM waves with high flexibility.

To generate symmetrical waveform, the ePWM's internal timer is configured in up-down count mode.

The set of formulae given below are all terms that relate the PWM frequency we want our switches to operate at and the time period(in clock cycles) of our fundamental voltage given to the induction motor. This relation is needed for us to configure the ePWM module to generate pulses at desired fundamental and PWM frequency. The variables involved in this conversion are mentioned below:

4.7.2 PWM Frequency Calculation

VARIABLE DEFINITIONS

Symbol	Description
F_{PWM}	Frequency of PWM (Hz)
T_{PWM}	Time period of PWM (seconds)
$TBCLK$	Time base clock (Hz)
T_{TBCLK}	Time period of time base clock (in seconds)
$TBPRD$	Timer period (in clock cycles)
$EPWMCLK$	ePWM module clock (in Hz)
$HSPCLKDIV$	High speed clock divider
$CLKDIV$	Clock divider

The period of the PWM signal can be calculated using the formula:

$$T_{PWM} = 2 \times TBPRD \times T_{TBCLK} \quad (11)$$

where $TBPRD$ is the time base period.

4.8 PWM FREQUENCY (F_{PWM})

The frequency of the PWM signal is defined as the inverse of the PWM period:

$$F_{PWM} = \frac{1}{T_{PWM}} \quad (12)$$

4.9 TIME BASE CLOCK (T_{TBCLK})

The Time Base clock is given by:

$$T_{TBCLK} = \frac{EPWMCLK}{HSPCLKDIV \times CLKDIV} \quad (13)$$

where:

- EPWMCLK is the clock frequency dedicated to the PWM module.
- HSPCLKDIV and CLKDIV are the dividers for the high-speed PWM clock.

4.10 TIMER PERIOD ($TBPRD$)

$$TBPRD = \frac{T_{PWM}}{2 \times T_{TBCLK}} \quad (14)$$

According to the FSAM20SH60A datasheet, a 15 kHz switching frequency is recommended for optimal performance. The dividers HSPCLKDIV and CLKDIV are both set to 1. Given that the EPWMCLK is derived from the system clock (SYSCLK) which operates at 200 MHz, the time base clock can be calculated as follows:

Given the PWM period T_{PWM} and the TBCLK frequency T_{TBCLK} , we need to solve for $TBPRD$ (Time Base Period Register). The calculations are as follows:

1. Calculation of T_{PWM} :

$$T_{PWM} = \frac{1}{15 \times 10^3} \text{ seconds}$$

This represents the period of the PWM.

2. Calculation of T_{TBCLK} :

$$TBCLK = \frac{200 \times 10^6}{1 \times 1} = 200 \times 10^6 \text{ Hz}$$

This is the frequency of the TBCLK (Time Base Clock).



Figure 4.12: ePWM block in Simulink

3. Solving for T_{BPRD} : With T_{PWM} and T_{TBCLK} known, we get 6667.

Figure 4.12 below shows the ePWM block in Simulink, which is used generate PWM waveforms from microcontroller.

Figure 4.13 below shows the ePWM module configuration.

4.10.1 Output Of SVPWM With Low Pass Filter

The fundamental low frequency wave is buried within the 15 kHz carrier wave. Thus passed through a low pass filter to extract the fundamental frequency and hardware setup is shown in Figure 4.14.

The output of the SVPWM with low pass filter is shown in Figure 4.15. The output is a SVPWM wave of 2 phases with a frequency 3hz.

4.10.2 Dead Band

Dead band is a time delay between the switching of the upper and lower switches in the inverter. This is necessary to prevent short circuiting of the DC bus. The dead band time is set in the ePWM module. The dead band time can be configured in the ePWM module, and it can be specified in terms of the number of clock cycles or in terms of time. The datasheet of FSAM20SH60A smart power module recommends a dead band time of atleast 3us.

An example of 20us dead band time is shown in Figure 4.16. The two waveforms shown are output of ePWM 1A and 1B which will be given to the upper and lower switches

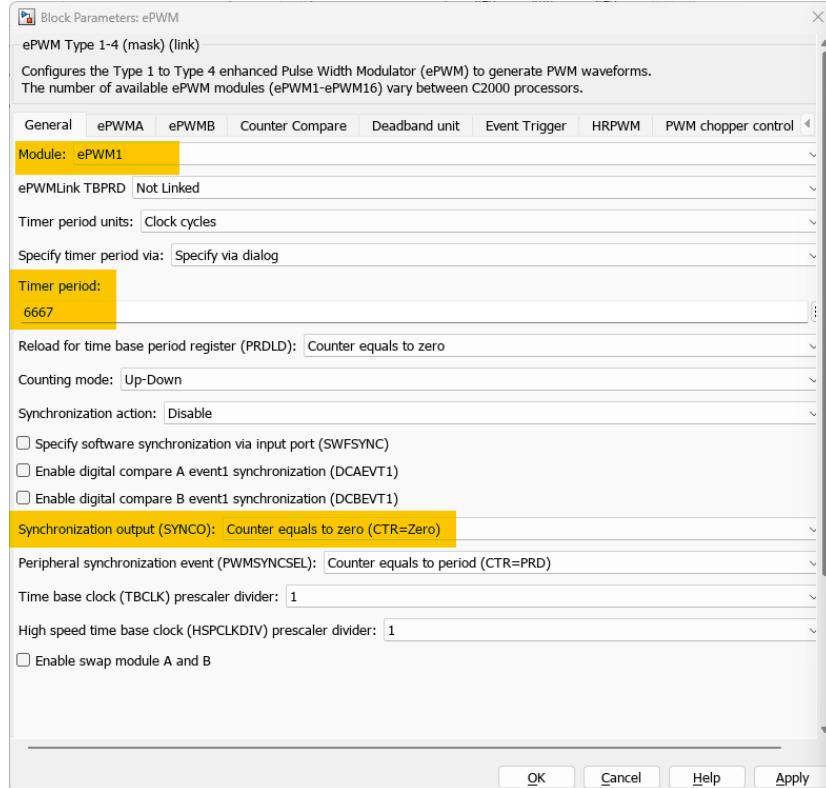


Figure 4.13: ePWM configuration in Simulink

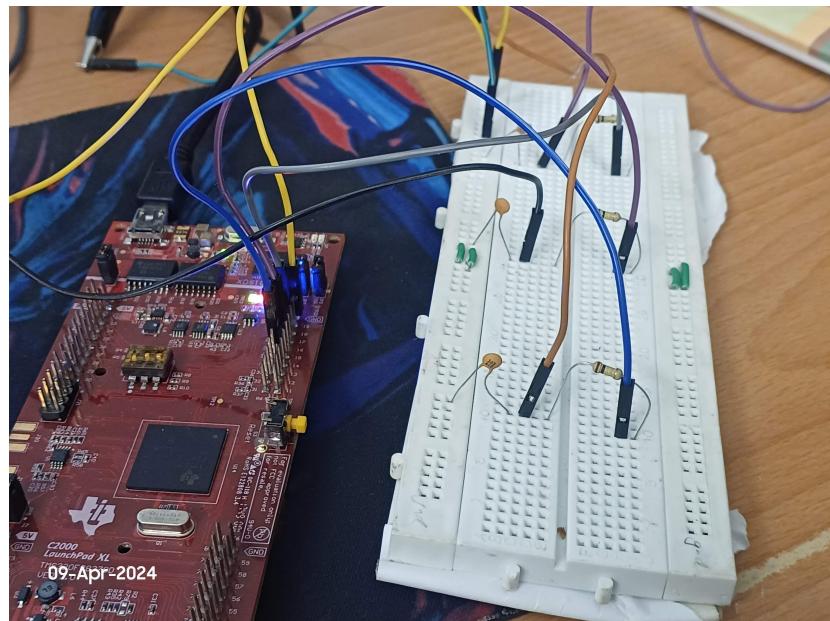


Figure 4.14: Hardware setup with RC filter and Launchpad

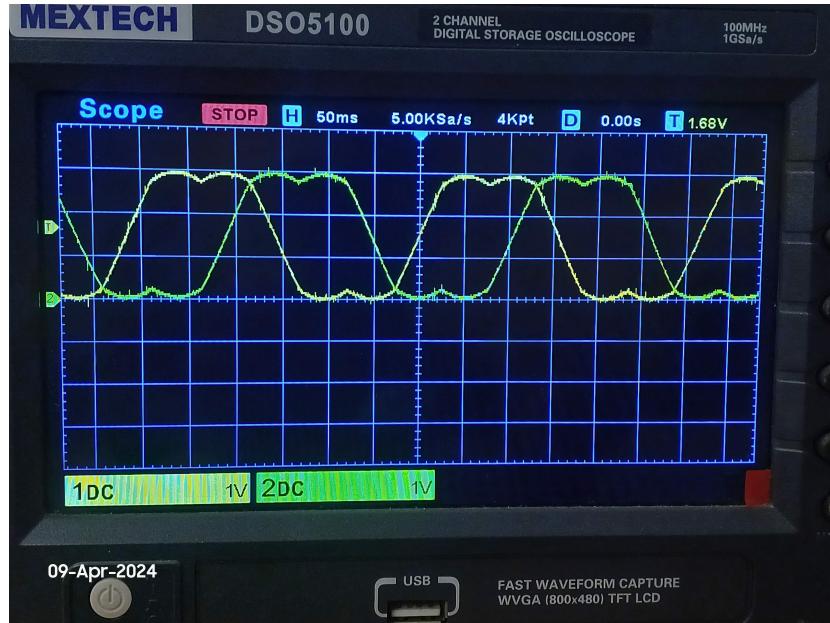


Figure 4.15: Output of SVPWM with low pass filter

of the inverter respectively.

4.11 HARDWARE SETUP FOR MOTOR CONTROL

4.11.1 DC BUS

The DC bus shown in Figure 4.17 is a critical component in motor control systems, serving as the primary power source for the inverter. In our project, we utilized a 50V DC bus, which was generated using a 230V AC to 48 V transformer and diode bridge rectifier. This DC bus was connected to capacitor banks of 450V 2350uF, ensuring stable, ripple free power delivery to the inverter.

4.11.2 INVERTER and Controller

The inverter and controller setup shown in Figure 4.18 is a key component in the motor control system, responsible for converting the DC power from the bus into AC power to drive the induction motor. The FSAM20SH60A intelligent power module was used to control the inverter, while the F28379D Launchpad served as the primary controller for

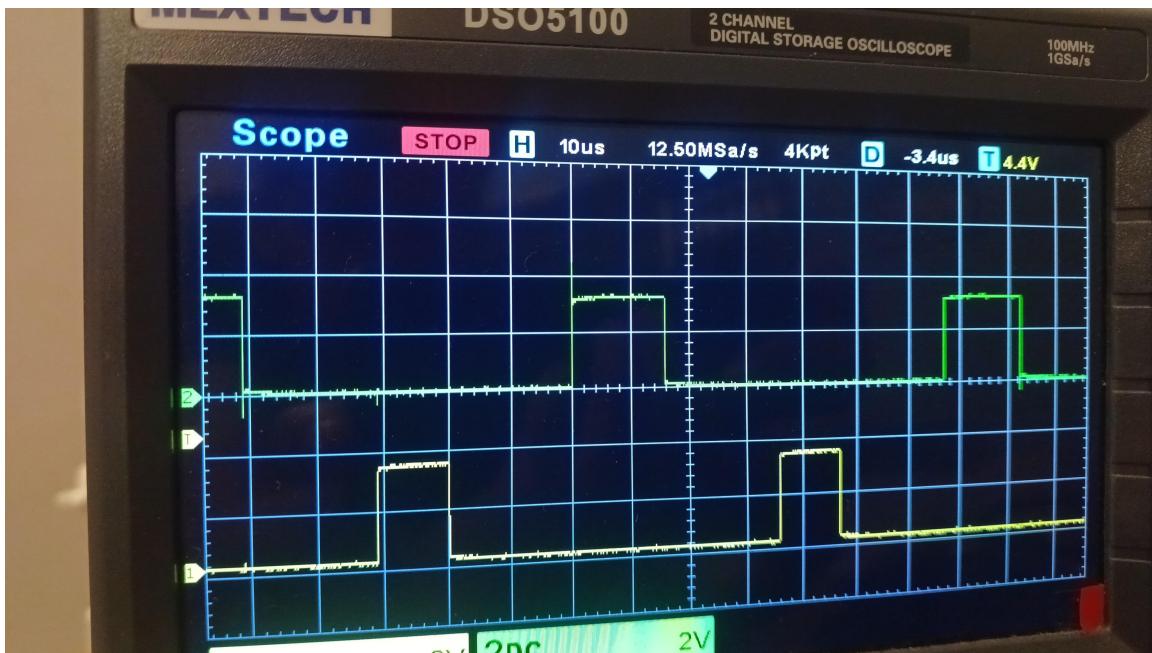


Figure 4.16: Dead band time

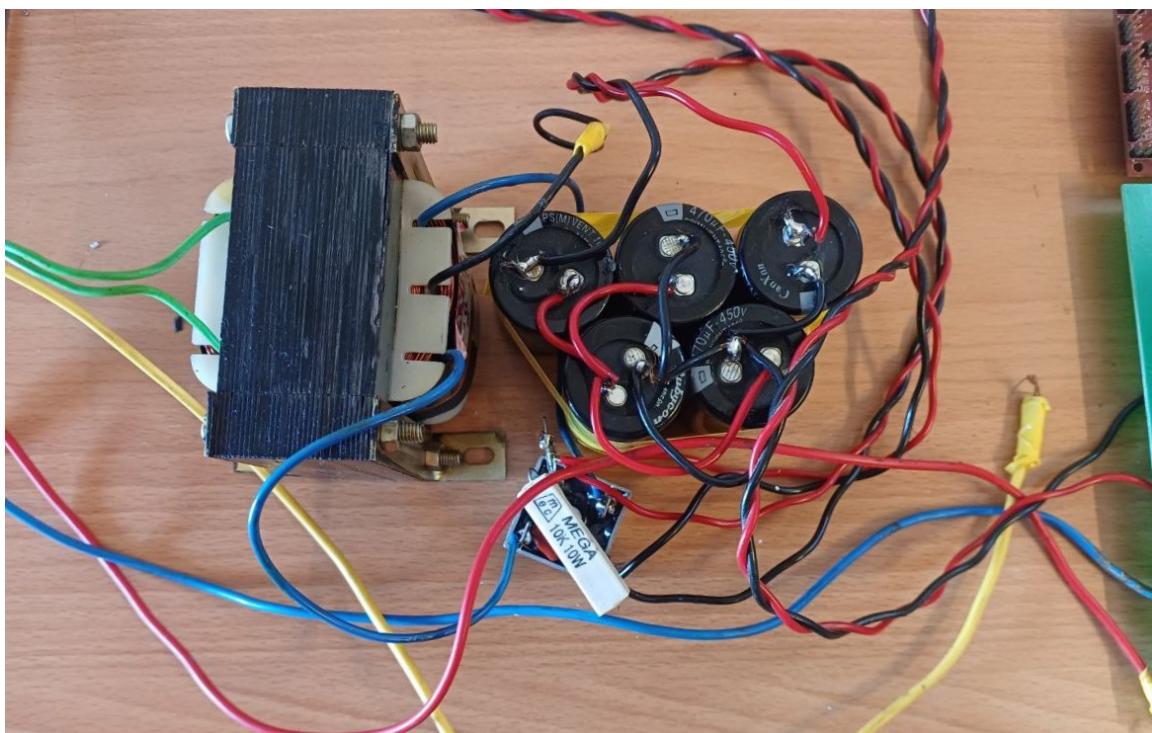


Figure 4.17: DC Bus Setup

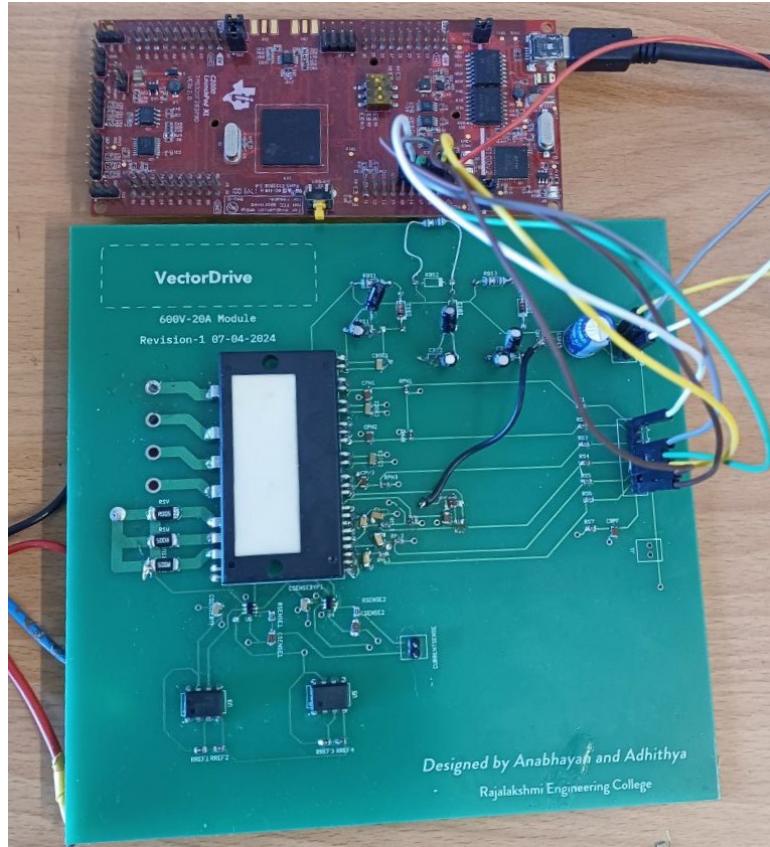


Figure 4.18: Inverter and Controller Setup

the system.

The figure 4.19 shows the complete hardware setup for the motor control system, integrating the induction motor, F28379D Launchpad, FSAM20SH60A intelligent power module, and the DC bus. This setup provides a comprehensive platform for developing and testing advanced motor control algorithms and strategies.

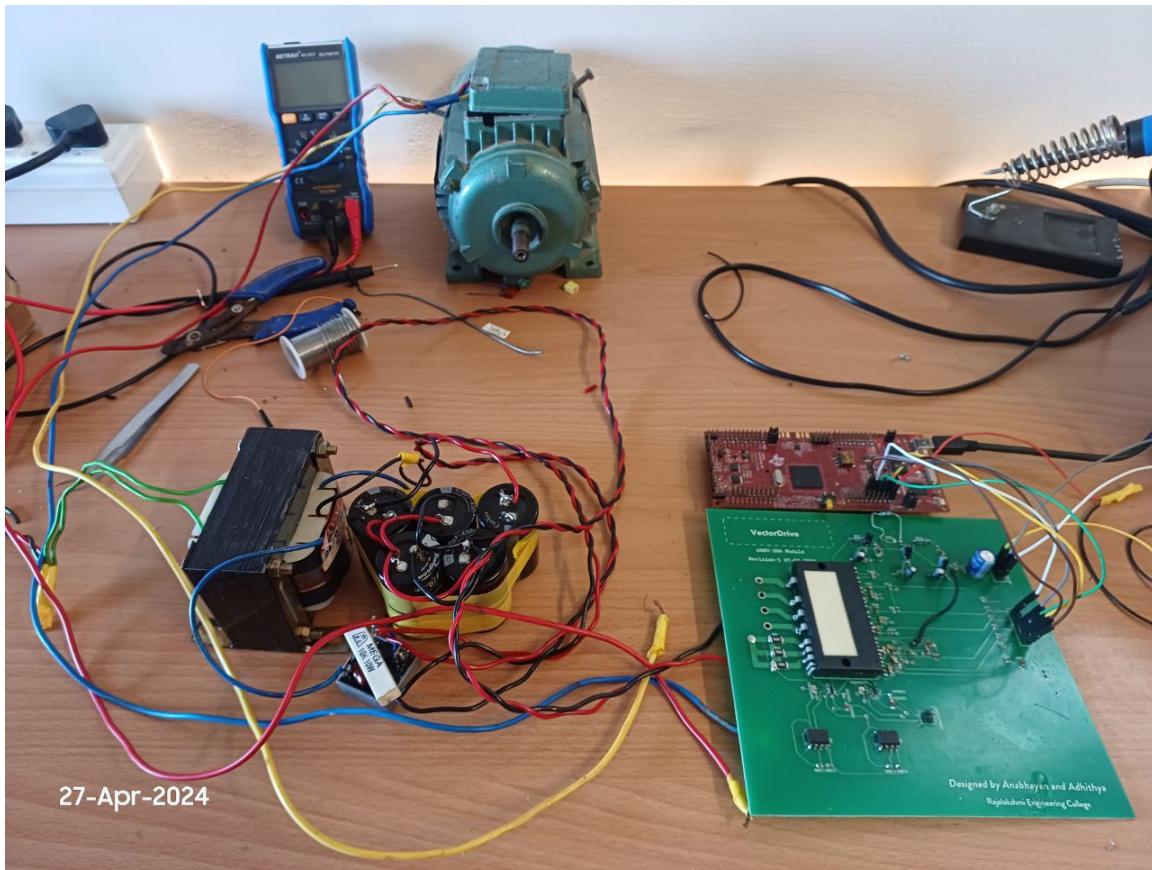


Figure 4.19: Complete Hardware Setup

CHAPTER 5

CONCLUSION

5.1 GENERAL

In conclusion, this thesis successfully demonstrates the design and implementation of an DSP based Sensorless Field Oriented Control of Induction Motor and proves that the smooth and precise control of speed and torque of vector control is unmatched by any other control strategies. The only input to the controller from the user for a given motor is the set speed and load applied to the shaft, while the control takes care of the rest and achieves the set speed in a quick and smooth manner driving the rated load even at low speeds.

The system effectively regulates key motor variables, achieving desired performance levels. Both the magnetizing current (I_d) and motor speed accurately track their respective reference values, demonstrating precise control. The I_d reference and feedback values converge to 0.2 pu, ensuring proper motor magnetization. Similarly, the motor speed closely follows its reference value of 0.5 pu. Furthermore, the load angle, a critical parameter for torque generation, stabilizes around 85-90 degrees. This indicates operation near the maximum torque per ampere condition, maximizing the motor's efficiency. The control system utilizes a carrier frequency of 15 kHz for pulse width modulation. It's important to note that the rated frequency for achieving the rated speed of the motor is 50 Hz. The control system dynamically adjusts the output frequency based on the desired speed reference, ensuring optimal performance across the operating range.

These results validate the FOC system's ability to achieve stable, controlled, and efficient operation of the AC induction motor under the simulated conditions.

5.2 SCOPE FOR FUTURE WORK

Future work for this thesis can focus on integrating position sensors and exploring advanced control techniques for further optimization. Though going sensorless reduces the hardware complexity and overall cost, it proportionally increases the software design complexity and possible reduction in position estimation accuracy due to errors in measurement of motor parameters. Using a rotary encoder with enough resolution will remove the possibility of inaccurate position estimations. Other control strategies include Direct Torque Control, Model Predictive Control and Indirect Field Oriented Control. Though Direct FOC is the overall best vector control algorithm, other mentioned control strategies have their own application specific advantages that can be further analysed and proper comparison between all control strategies can be recorded.

REFERENCES

1. Chen, Wen Zhuo, et al. "Simulation of Permanent Magnet Synchronous Motor Field Oriented Vector Control System." *Applied Mechanics and Materials*, vol. 672–674, Trans Tech Publications, Ltd., Oct. 2014, pp. 1234–1237.
2. D Arun Dominic, Thanga Raj Chelliah, Analysis of field-oriented controlled induction motor drives under sensor faults and an overview of sensorless schemes, *ISA Transactions*, Volume 53, Issue 5, 2014, Pages 1680-1694, ISSN 0019-0578.
3. D. Xu, B. Wang, G. Zhang, G. Wang and Y. Yu, "A review of sensorless control methods for AC motor drives," in *CES Transactions on Electrical Machines and Systems*, vol. 2, no. 1, pp. 104-115, March 2018.
4. E. S. Tez, "A simple understanding of field-orientation for AC motor control," *IEE Colloquium on Vector Control and Direct Torque Control of Induction Motors*, London, UK, 1995, pp. 3/1 -3/4.
5. Yusivar, N. Hidayat, R. Gunawan and A. Halim, "Implementation of field oriented control for permanent magnet synchronous motor," *2014 International Conference on Electrical Engineering and Computer Science (ICEECS)*, Kuta, Bali, Indonesia, 2014, pp. 359-362.

WEB REFERENCES AND VIDEOS

1. Teaching Old Motors New Tricks - An educational resource by Texas Instruments, outlining modern methods for enhancing older motor systems.
View at: <https://www.youtube.com/watch?v=fpTvZlnrsP0>

2. Electrical Machines and Drives - Theodore Wiliidi's comprehensive text, a foundational reference in the field of electrical engineering.
3. Control Systems Engineering - A seminal book by Norman Nise that delves into the principles and applications of control systems.
4. Electric Motors and Drives (Fifth Edition) - Austin Hughes and Bill Drury's book covering pages 261-305 for an in-depth exploration of motor technology. Published in 2019.
5. Motor Control Series by Matlab - Provides a structured learning path for motor control systems.

Available at: <https://www.youtube.com/watch?v=gNpoTPzEkco>

6. Introduction to EPWM - A general introduction to the concept of EPWM, presented in an accessible format.

View at: <https://www.youtube.com/watch?v=mmvMck6eMsk>

7. Sinusoidal Pulse Width Modulation (SPWM) - An informative video detailing SPWM and its utilities.

Watch at: https://www.youtube.com/watch?v=bcSSB_yHF0C

8. Tutorial on EPWM - Well-regarded for its clarity and instructive value.

<https://www.youtube.com/watch?v=YGjyaA84MwY>

9. Brief EPWM Tutorial - A brief but instructive EPWM tutorial; the initial five minutes are particularly insightful.

Watch at: <https://www.youtube.com/watch?v=CL3woGx9d0U>

10. Duty Cycle Variations with ADC - A resource explaining the adjustments of duty cycles in response to analog-to-digital converter inputs.

Available at: <https://www.youtube.com/watch?v=XLp08Nhev48>

11. Introductory Guide to C2000 Microcontroller - An introductory guide to the capabilities and features of the C2000 microcontroller from Texas Instruments.

View at: <https://www.youtube.com/watch?v=owC7x7wudx8>

12. FOC in Induction Motors - *FOC IM Explain Fast and Crisp* - A video offering a concise explanation of Field-Oriented Control (FOC) in Induction Motors.

Available at: <https://www.youtube.com/watch?v=uNs1ScKD07I>

13. FOC in PMSM - Detailed exposition on the application of Field-Oriented Control (FOC) in Permanent Magnet Synchronous Motors (PMSM).

Watch at: <https://www.youtube.com/watch?v=wxYTLbYfBP0>

14. Calibrating ADC offset - Practical guide on how to calibrate the ADC offset, an essential step in ensuring the accuracy of analog-to-digital conversions.

View at: <https://www.youtube.com/watch?v=Lb2VpRjqrXI>