Project Report

(Internship Semester January–June)

Design of Front end converter using SVPWM technique

Submitted by

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Under the Guidance of

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TO WHOM SO EVER IT MAY CONCERN

This is to certify that Shashank Agarwal, a 3rd year student of Bachelor of Engineering in Electrical Engineering at Punjab Engineering College, Chandigarh, interned at Statcon Electronics India Limited. Shashank worked with us from Jan 10, 2024 to July 10, 2024, in a paid, full-time capacity.

We wish him success in his future endeavors.

Sincerely,
On behalf of Statcon Electronics India Limited

Manoj Kumar
Assistant Manager – HR & Admin

Declaration

I hereby declare that the project work entitled "Design of Active Front End" is an authentic record of my own work carried out at Statcon Electronics India Ltd as requirements of six months project semester for the award of degree of B.E./B.Tech. Electrical Engineering, Punjab Engineering College (Deemed to be University), Chandigarh, under the guidance of Mr.Sarv Parteek Singh and Dr.Loveleen Kaur Taneja, during January to June, 2024.

Date: July 13, 2024

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Certified that the above statement made by the student is correct to the best of our knowledge and belief.

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I extend my heartfelt gratitude to Mr.M.S. Saini, Director of our company, for his continuous encouragement and belief in my abilities. His support has been instrumental in navigating through various aspects of the project and ensuring its successful completion. Additionally, it is worth mentioning that Mr.M.S. Saini is an alumnus of PEC, from the Electrical Engineering batch of 1978.

Furthermore, I would like to express my sincere appreciation to Dr.Krishna Dora for his invaluable guidance in the development of the SVPWM Inverter and his assistance with MATLAB. His expertise and mentorship have been indispensable in overcoming technical hurdles and achieving project milestones.

I am sincerely thankful to each of them for their contributions, which have played a significant role in the successful completion of this project.

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1. Summary

I got the opportunity to do my internship at Statcon Electronics India Ltd. Statcon Electronics established in 1986 is one of India's largest ISO 9001-20151 certified manufacturer of Static energy Conversion system. During my internship at Satcon Electronics India Ltd, Noida, I was first assigned to explore Space Vector Modulation technique and then make a simulation for a front end converter using Space Vector Modulation. I was part of the Embedded Software team and my task was to develop a control algorithm for the front end converter.

The aim of the project to design a Active Front End converter for a Hybrid inverter,aiming to enhance its efficiency and performance while reducing harmonic distortions and improving the power factor.

1.1 Timeline

My internship at Statcon Electronics India Ltd started on 10th January, 2024. My mentor gave me the task of exploring Space Vector Modulation and developing control algorithm for the front end converter. This timeline will briefly explain the course of my internship from beginning to end.

1.1.1 January

In January, I started learning about Space Vector Pulse Width Modulation (SVPWM). This involved understanding two important things: the Clarke and Park transforms. These transforms help to change three-phase voltages into a simpler two-dimensional form, making it easier to control three-phase systems. The Clarke transform turns three-phase voltages into two-phase parts, while the Park transform changes these parts into a fixed frame of reference. I also learned about space vectors, which show how the three-phase voltages combine. This knowledge helped me understand SVPWM better. It's a technique that uses space vectors to control how inverters produce voltage. This exploration gave me a better grasp of how SVPWM works and its uses in power electronics.

1.1.2 Feburary

During February, I immersed myself in the study of the Clarke and Park transforms, essential mathematical tools used in analyzing three-phase electrical systems.The Clarke transform simplifies three-phase voltages into two-phase components, making it easier to understand and analyze complex electrical systems. Similarly, the Park transform further refines these components into a fixed frame of reference, streamlining the analysis and control of electrical signals. Alongside theoretical exploration, I practically experimented

by developing Python code to implement and test these transformations. This hands-on approach not only deepened my understanding of the transforms but also provided valuable insights into their real-world applications and implementation challenges.

1.1.3 March

During March, I worked on developing and testing a three-phase Phase-Locked Loop (PLL) algorithm using Python. This algorithm used the Clarke and Park transforms to precisely estimate the angle of the space vector in the three-phase system. Following the initial testing phase of the PLL algorithm in Python, I transitioned to Simulink/MATLAB for further simulation. Within the Simulink environment, I used MATLAB function blocks to implement the PLL algorithm. Once this was completed, I proceeded to make a three-phase inverter in Simulink using IGBT components. Leveraging MATLAB function blocks and the output of the PLL, I then generated gate timing signals for the Front end of the inverter, ensuring precise control and synchronization of the electrical signals.

1.1.4 April

In April, I worked toward fine-tuning the Proportional-Integral (PI) controller for the Phase-Locked Loop (PLL) using the Ziegler–Nichols method. This involved adjusting the parameters of the PI controller to optimize the performance of the PLL algorithm. By employing the Ziegler–Nichols method, I aimed to achieve stability and responsiveness in tracking and synchronizing the phase of electrical signals effectively. Additionally, I implemented a control loop in MATLAB function blocks to measure the current flowing from the front end to the grid. This control loop allowed for the adjustment of the output voltage to either draw or supply the desired current, depending on the system requirements.

1.1.5 May

In May, I completed the simulation and proceeded with the actual implementation of the front end on hardware. I began by selecting a suitable microcontroller with DSP capability, opting for the STM32F411 microcontroller. Then, I initiated the coding process, developing functions for voltage transformations, PID controller, and Phase Lock Loop (PLL). Additionally, I integrated unit testing using Unity to test individual functions of the code. Moreover, I created a native target to provide sample signals to the code, generating output graphs for viewing. This approach allowed me to test my code without the need for a microcontroller.

1.1.6 June

In June, I relocated from the Noida office to the Hyderabad office to continue developing both the code and hardware. While in Hyderabad, I familiarized myself with the standard coding structure required for our projects and proceeded with the development process.
I began writing the code for the microcontroller, During this phase, I learned about Direct Memory Access (DMA) and interrupts, which I used to sample the input voltage. Using these sampled voltages as reference values, I generated the Space Vector output in the form of Pulse Width Modulation (PWM) signals from the microcontroller. This approach ensured precise and efficient control of the system.

2. Introduction

An active front-end (AFE) converter, is a grid interface converter that transfers power between an energy source and the utility grid, and between the utility grid and a load. It's a controllable rectifier that can exchange power between AC and DC power in both directions, and can regenerate power to the mains to reduce power costs.

2.1 Problem Statement

My team at Statcon Electronics India Ltd has been focusing on on enhancing the efficiency and performance of front-end converters. Presently, most active front-end converters utilize Silicon Controlled Rectifiers (SCRs) for rectification, employing a conventional 6-pulse converter configuration. My task was to explore and design a active front-end using Insulated Gate Bipolar Transistors (IGBTs) as alternatives to SCRs in the rectification process.

The primary objective of this project is to investigate the feasibility and advantages of using IGBTs instead of SCRs for rectification in active front-end converters. Specifically, we aim to implement a Space Vector Pulse Width Modulation (SVPWM) technique to control the IGBTs effectively. This technique offers precise control over the switching patterns of the IGBTs, allowing for optimized power conversion and reduced harmonic distortion.

Furthermore, the project involves the development of a sophisticated control algorithm to manage the operation of the IGBTs. This algorithm must facilitate seamless transition between pulling current from the grid (rectification mode) and supplying current to the grid (regeneration mode). The control system should ensure stable and efficient operation under varying load conditions while maintaining compliance with grid standards and regulations.

2.2 Overview

A three-phase AC to DC converter is essential for many power electronics system such as Variable frequency drive (VFD), battery charger, uninterruptible power supplies (UPS). Traditionally diode rectifiers or thyristor rectifier are used for AC to DC conversion, both these rectifiers behave as non- linear loads. The currents drawn by the rectifiers include a fundamental component and harmonic components. The voltage drop across the line inductance due to the harmonic currents distorts the mains voltage. Consequently, the other loads connected to the mains are also fed with a distorted voltage.

2.2.1 Traditional Rectifier

Diode rectifier, depicted in Figure 2.1, produces a constant DC voltage, which is a function of the system voltage. A thyristor based rectifier can produce a variable DC voltage. But, both these topology behave as non-linear loads.

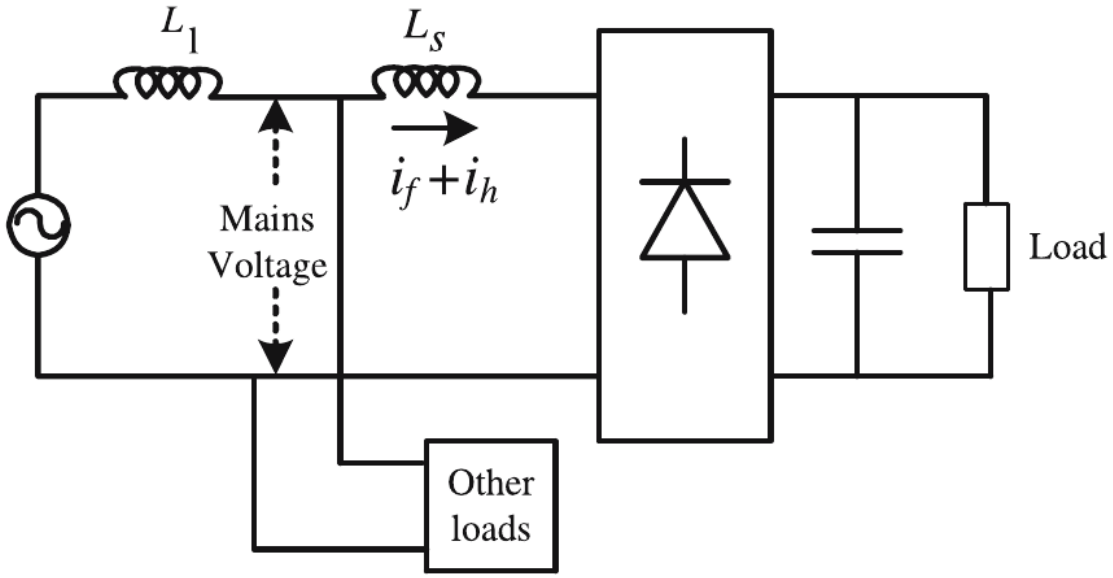


Figure 2.1: AC to DC Conversion using Diode Rectifier.

2.2.2 IGBT Rectifier

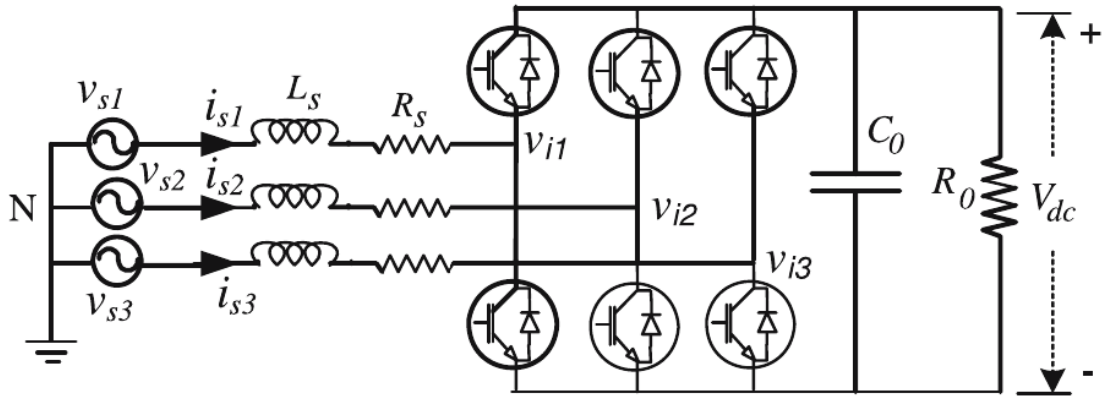


Figure 2.2: Schematic diagram of a front-end converter (FEC)

IGBT Rectifer, depicted in Figure 2.2, draws near sinusoidal current from grid. The power factor as well as DC Voltage can be adjusted. Since it is connected to line side it is called line side or front end converter.

The converter consists of a three-phase bridge, a high capacitance on the dc side and a three-phase inductor in the line-side. The voltage at the mid point, V_i is pulse width modulated (PWM) in nature. The voltage consists of a fundamental component (at line frequency) besides harmonic components around the switching frequency of the converter. Being at high frequencies, these harmonic components are well filtered by the line inductor. Hence the current is near sinusoidal. The fundamental component of V_i controls the flow of real and reactive power.

2.2.3 Vector Control

Vector control is a popular method for control of three-phase induction motors. The basic idea of this scheme is to control the flux producing and the torque-producing components of motor current. The outer control loop controls the speed of the motor, while the inner loop controls the components of current vector, which correspond to torque and flux. Similar control approach can be used for FEC also. Here, the three-phase grid voltages and line currents are converted into an equivalent two-phase system, called stationary reference frame . These quantities are further transformed into a reference frame called synchronous reference frame, which revolves at the grid frequency .

2.2.4 Space Vector Modulation

This technique, also known as Space Vector Pulse Width Modulation (SVPWM), is a method used to generate the switching signals for the IGBTs in the AFE converter. It offers precise control over the IGBT switching patterns by synthesizing the desired output voltage as a combination of multiple voltage vectors. SVM has eight space vectors, other space vectors are synthesized by alternating active and zero vectors over a switching period.

2.3 Challenges

I faced many challenges in developing a Active front-end converter. Firstly, distinguishing between Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) posed confusion due to their perceived similarity in operational principles. Secondly, reconciling the non-zero resultant vector in SVPWM with the traditional understanding of three-phase systems, where the vector sum equals zero, required conceptual clarification to ensure accurate system design and analysis. Another challenge was comprehending how rectification and regeneration can occur through the same IGBT bridge, as it involved bidirectional power flow management. Additionally, not knowing how to write code in MATLAB was another challenge, but learning it opened up new possibilities for simulating and analyzing our AFE converter designs.

3. Work

3.1 Simulation

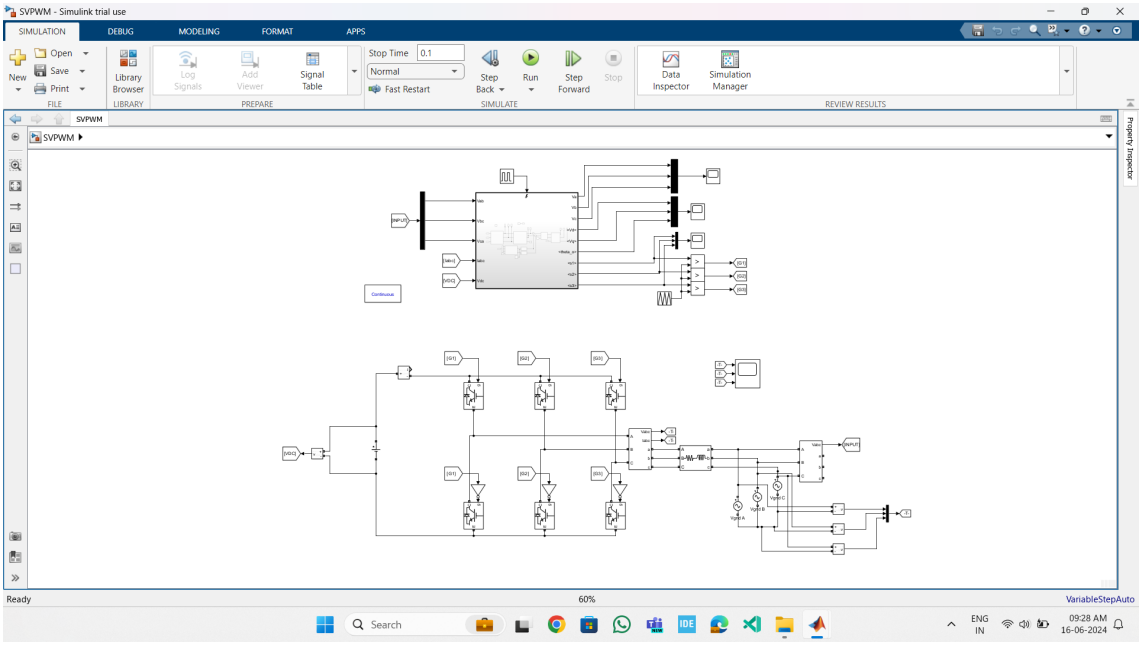


Figure 3.1: Simulation

Before initiating the implementation phase, it was imperative to conduct a comprehensive simulation of the front end using Simulink/MATLAB. The simulation setup involved importing a three-phase source from MATLAB and configuring the necessary parameters for voltage and current measurements.

3.1.1 MATLAB Function Blocks in Simulation

To emulate the behavior of a microcontroller in the simulation environment, MATLAB function blocks were extensively utilized. These function blocks provided a familiar coding environment, resembling the programming paradigms employed in microcontroller firmware development. By encapsulating custom algorithms and control logic within MATLAB function blocks, it was possible to simulate complex control strategies and signal processing techniques with ease. This approach not only facilitated rapid prototyping and testing but also provided invaluable insights into the real-time behavior of the system. The use of MATLAB function blocks bridged the gap between simulation and implementation, enabling seamless transition from design validation to hardware deployment.

3.1.2 Control System

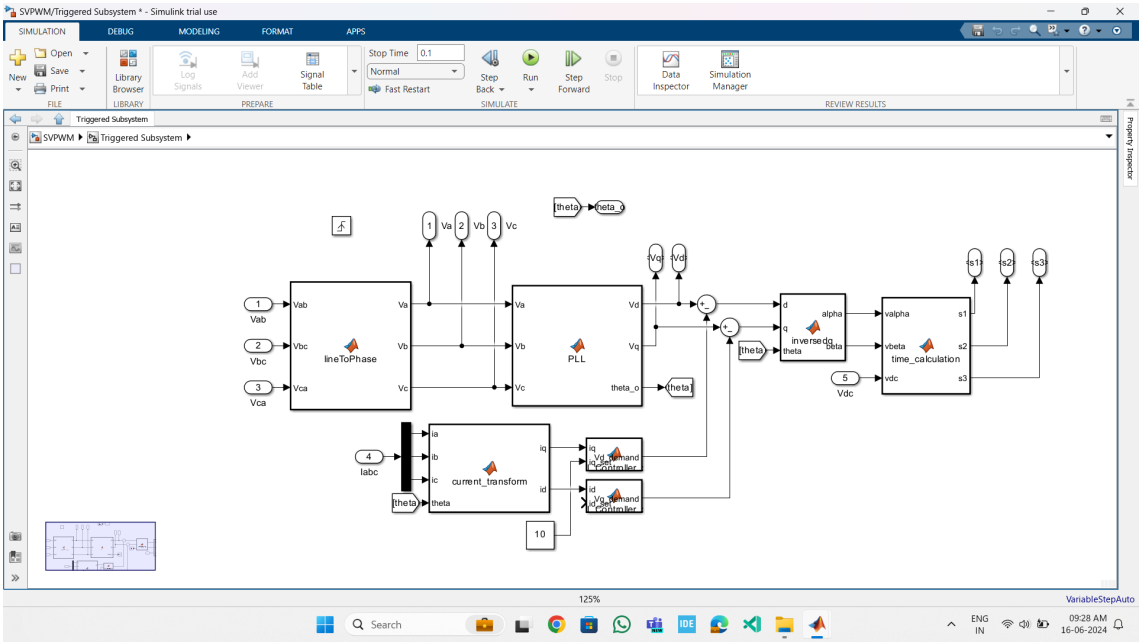


Figure 3.2: Control System

Voltage Transformation

Transform the measured line voltages from the three-phase source into the alpha-beta frame using the Clarke transform. This transformation facilitates easier analysis and control of the three-phase system. The Clarke transform converts three-phase voltages into two orthogonal components (alpha and beta), simplifying the analysis of the system's dynamics and making it easier to implement control strategies.

Phase-Locked Loop (PLL)

Incorporate a Phase-Locked Loop (PLL) block to convert the voltages from the alpha-beta frame to the dq rotating reference frame. Additionally, the PLL provides the angle theta of the voltage vector, crucial for subsequent control strategies. The PLL ensures synchronization with the grid by maintaining a constant phase relationship, which is vital for accurate control and stability of the system.

Current Measurement and Transformation

Measure the line current flowing into the front end, and using Clarke and Park transform blocks, convert it to the dq reference frame. Utilize the angle theta obtained from the PLL for this transformation. The dq reference frame allows for decoupled control of the direct and quadrature components of the current, enabling more precise control of the active and reactive power.

Current Regulation

Regulate the current flowing into the front end to ensure stable operation and adherence to system constraints. Employ two Proportional-Integral (PI) controllers to compare the measured current to a predetermined set current value and generate control signals for current regulation. The PI controllers adjust the control signals to minimize the error between the measured and desired current values, ensuring the system operates within the desired parameters.

Voltage Calculation and Transformation

Add the control signals (delta Vq and delta Vd) obtained from the PI controllers to the Vq and Vd components obtained from the PLL. Convert these voltages back to the Clarke frame using the inverse Park transform. This step integrates the control efforts with the system's voltages, transforming the controlled voltages back into the stationary reference frame for further processing and application.

Gate Timing Calculation

Utilize the voltages calculated in the previous step (V alpha* and V beta*) to determine gate timings for the three-phase active front end. These gate timings dictate the switching patterns of the Insulated Gate Bipolar Transistors (IGBTs), essential for controlling the flow of current through the front end. The precise timing of the IGBT switching is crucial for maintaining the desired current and voltage waveforms, ensuring efficient and stable operation of the power conversion system.

3.1.3 Power System

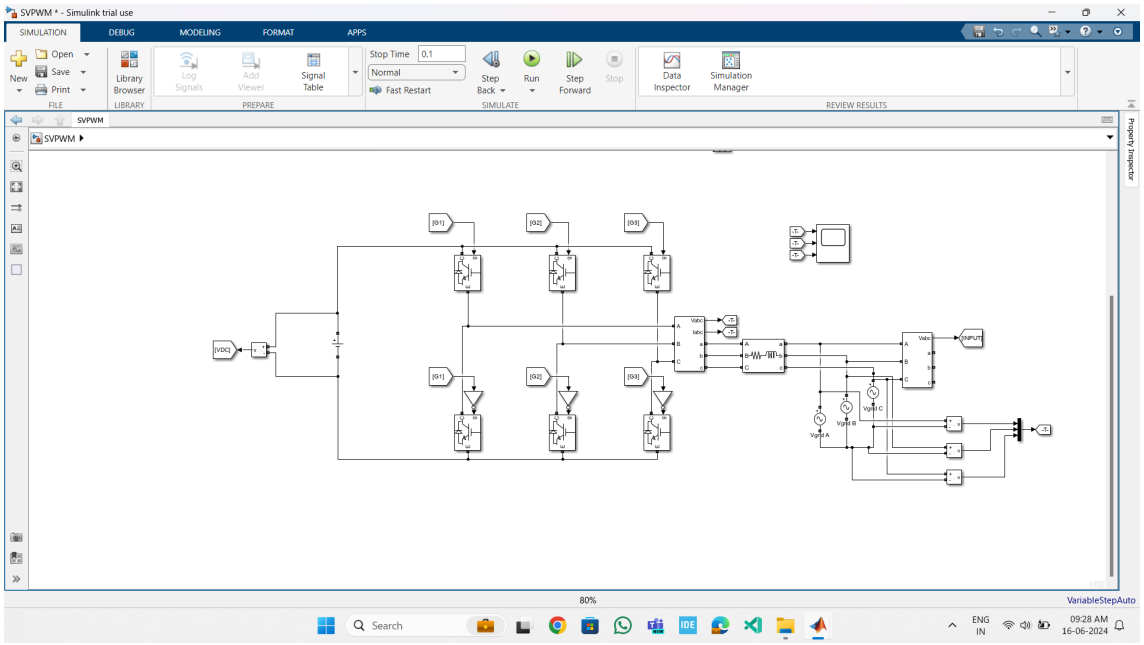


Figure 3.3: Power System

Three-Phase AC Source

The Three-Phase AC Source serves as the input power to the system.It provides three sinusoidal voltage waveforms with a 120-degree phase difference between each phase.The amplitude and frequency of the AC source are determined based on the grid specifications or the application requirements.

Three-Phase IGBT Bridge

The Three-Phase IGBT Bridge is the primary power conversion and control element in the system. It consists of six Insulated Gate Bipolar Transistors (IGBTs) arranged in a three-phase bridge configuration. The IGBTs are switched in a complementary manner to modulate the voltage across the load.

The IGBT bridge controls the flow of current from the AC source to the load by switching the IGBTs on and off at precise intervals. This switching action enables the conversion of AC power from the source to DC power, which can be further conditioned or inverted as per the requirements of the application.

Additionally, the gate timing signals for the IGBTs are generated based on the control signals calculated by the control system. These gate timing signals dictate the switching pattern of the IGBTs, ensuring the desired current and voltage waveforms are maintained for efficient and stable operation of the power conversion system.

3.2 Implementation

After completing the simulation using Simulink/MATLAB to validate the system design and control strategies, the project transitioned to the implementation stage on a microcontroller. This phase focused on translating theoretical concepts into practical application. This section includes the selection process of the microcontroller, development of essential transformation functions in C, and the integration of hardware components such as timers, Direct Memort Access (DMA), and Analog to Digital Converter (ADC) for accurate system monitoring and control.

3.2.1 Microcontroller Selection

The first step in the implementation phase was choosing an appropriate microcontroller for the project. After evaluating several options, the STM32F411 was selected due to its Digital Signal Processing (DSP) and Floating Point Unit (FPU) capabilities. These features allowed us to run the Proportional-Integral-Derivative (PID) loop at a high frequency of 10kHz, providing 200 samples per cycle. This high sampling rate was crucial for achieving precise control and stability in the system.

3.2.2 Implementation of Voltage transform functions

To handle the transformations required for the control algorithms, I implemented the Clarke and Park transform functions in C. The process began by creating an array with synthetic values to simulate the inputs. These values were then fed into the custom transformation functions. The output was verified using GNUPLOT to ensure the accuracy of

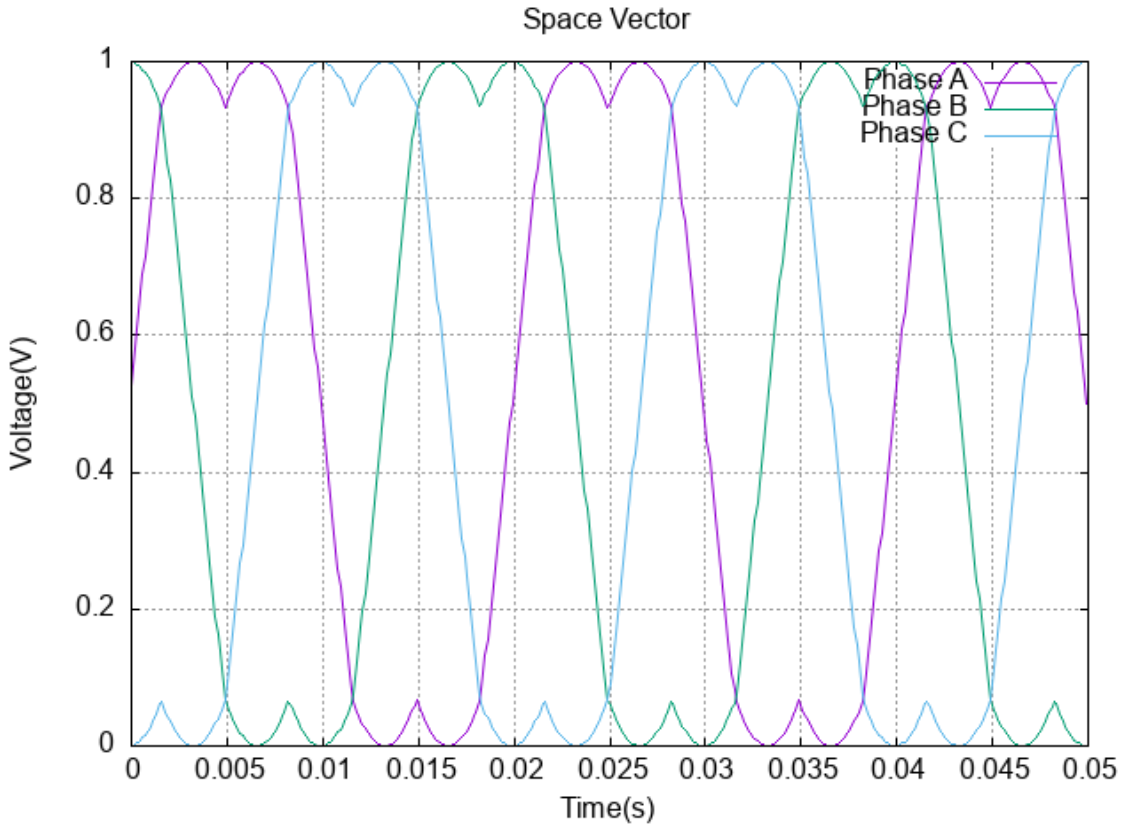


Figure 3.4: Space Vector plotted using GNUPLOT

the transformations. This step was essential to validate the mathematical operations and ensure the functions were performing as expected.

3.2.3 Microcontroller Programming and Testing

With the transformation functions ready, I proceeded to program the STM32F411 microcontroller. This phase involved a deep dive into various aspects of the microcontroller, including timers, Direct Memory Access (DMA), and Analog-to-Digital Converters (ADC).

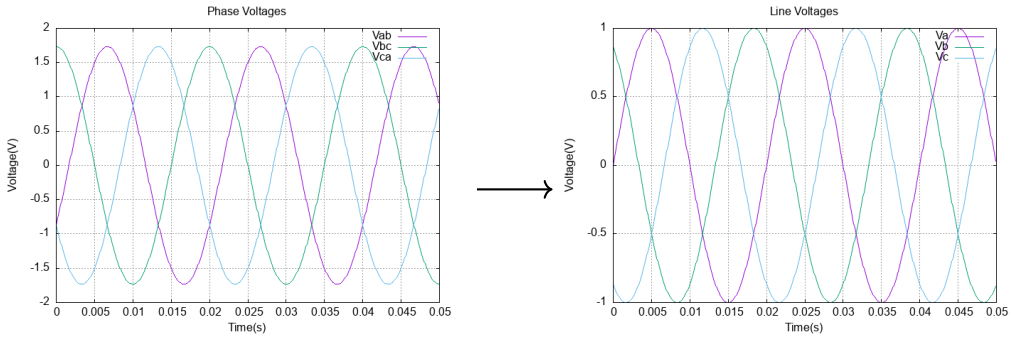
- **ADC Sampling**: I utilized the ADC to sample the voltage values from the system. This real-time data acquisition was critical for the subsequent control processes.
- **Transformation and Modulation**: The sampled voltage values were processed using the previously developed Clarke and Park transform functions. This step generated the necessary parameters for Space Vector Modulation (SVM).

The integration of these components allowed for the generation of space vector modulated waves, essential for controlling the power conversion system effectively. Each part of this process was meticulously tested to ensure reliability and accuracy, laying a strong foundation for the successful deployment of the control system.

4. Details of work

In this sections I will provide a detailed explanation of each component and process involved in the implementation phase of the project. Before diving into the details, it's crucial to establish a foundational understanding of key concepts that simplify the analysis and control of three-phase circuitry.

4.1 Phase-Line Transformation



(a) Phase Voltages (b) Line Voltages

4.1.1 Why Measure Phase Voltage?

In three-phase electrical systems, the measurement of phase voltages becomes critical due to the unavailability of the neutral point. This unavailability means that direct measurement of line voltages is not feasible. Phase voltage refers to the voltage measured across a single component within the three-phase system, typically between a phase (live) wire and the neutral point. These measurements are essential because they are the only voltages directly accessible within the system. Despite this, most voltage transformations and analyses are conventionally performed on line voltages, which represent the voltage difference between any two phases in the system. To bridge this gap, it is imperative to convert the measured phase voltages to line voltages using precise voltage transformations.

4.1.2 Need for Conversion from Phase to Line Voltage

In a three-phase system, the primary objective is to regulate both the line current and line voltage accurately. Line voltages, which are the voltages between any two phases, are crucial for determining the overall performance and stability of the system. However, since we are limited to measuring phase voltages, a reliable conversion mechanism is

necessary to translate these measurements into line voltages. This conversion is essential for achieving accurate control and analysis of the system's electrical parameters. By converting phase voltages to line voltages, we can apply standard voltage transformation techniques and ensure that the control strategies and safety mechanisms are based on accurate and relevant data.

4.1.3 Why Simply Dividing by the Square Root of 3 is Insufficient

A common misconception is that dividing the measured phase voltage by the square root of 3 will yield the correct line voltage. This approach is based on the RMS (Root Mean Square) values and is only accurate for calculating the magnitude of the line voltage under steady-state, balanced conditions. The relationship $phase\ voltage = \sqrt{3} \times line\ voltage$ holds true only for the RMS values of sinusoidal voltages in a perfectly balanced system. However, for dynamic applications, such as those involving digital signal processing (DSP), we require instantaneous line voltages rather than just RMS magnitudes.

Instantaneous voltages account for the real-time variations and phase differences that occur in practical systems. Therefore, a more robust method is necessary to obtain these instantaneous values accurately. To address this requirement, we use a transformation matrix that accurately converts the phase voltages to line voltages. The transformation matrix employed is:

$$T_{line} = \begin{bmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{-1}{3} & \frac{1}{3} & 0 \\ \frac{-1}{3} & \frac{-2}{3} & 0 \end{bmatrix}$$

This matrix provides a precise method to convert the three measured phase voltages into their corresponding line voltages, ensuring that the instantaneous values required for DSP and other real-time control applications are accurately obtained. This approach eliminates the inaccuracies associated with simple RMS-based conversion and allows for a more accurate representation of the system's electrical characteristics in real-time operations.

4.1.4 Derivation of the Transformations

For this conversion, we need to define a matrix, so let's look at the derivation for such a matrix.
Let V_a, V_b, V_c be the phase voltages given by:

$$V_a = \sin(\omega t)$$

$$V_b = \sin(\omega t - 120^\circ)$$

$$V_c = \sin(\omega t + 120^\circ)$$

The line voltages V_{ab}, V_{bc}, V_{ca} are given by:

$$V_{ab} = V_a - V_b$$

$$V_{bc} = V_b - V_c$$

$$V_{ca} = V_c - V_a$$

Also, we know that:

$$V_a + V_b + V_c = 0$$

Let us assume two matrices: P, representing phase voltages, and L, representing line voltages:

$$P = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$L = \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix}$$

Let T be a transformation matrix from P to L:

$$L = T \cdot P$$

We can define T as:

$$T = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

Since the inverse of T does not exist, we redefine it as:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \\ 0 \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 & 1 \\ 0 & 1 & -1 & 1 \\ -1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ 0 \end{bmatrix}$$

Taking the inverse of T:

$$T^{-1} = \begin{bmatrix} \frac{2}{9} & -\frac{1}{9} & -\frac{4}{9} & \frac{1}{3} \\ -\frac{4}{9} & \frac{2}{9} & -\frac{1}{9} & \frac{1}{3} \\ -\frac{1}{9} & -\frac{4}{9} & \frac{2}{9} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 \end{bmatrix}$$

Solving the matrix:

$$V_a = \frac{2}{9}V_{ab} - \frac{1}{9}V_{bc} - \frac{4}{9}V_{ca}$$

$$V_b = -\frac{4}{9}V_{ab} + \frac{2}{9}V_{bc} - \frac{1}{9}V_{ca}$$

$$V_c = -\frac{1}{9}V_{ab} - \frac{4}{9}V_{bc} + \frac{2}{9}V_{ca}$$

We also know that $V_{ab} + V_{bc} + V_{ca} = 0$, so:

$$V_{ca} = -V_{ab} - V_{bc}$$

Thus:

$$V_a = \frac{2}{3}V_{ab} + \frac{1}{3}V_{bc}$$

$$V_b = -\frac{1}{3}V_{ab} + \frac{1}{3}V_{bc}$$

$$V_c = -\frac{1}{3}V_{ab} - \frac{2}{3}V_{bc}$$

So, we can define the transformation matrix as:

$$T_{line}^{-1} = \begin{bmatrix} \frac{2}{9} & -\frac{1}{9} & -\frac{4}{9} \\ -\frac{4}{9} & \frac{2}{9} & -\frac{1}{9} \\ -\frac{1}{9} & -\frac{4}{9} & \frac{2}{9} \end{bmatrix}$$

4.2 Clarke transform

The alpha-beta transform, also known as the Clarke transform, is a fundamental mathematical tool used to simplify the analysis of three-phase electric machines. It is named after Edith Clarke, who published papers in 1937 and 1938 introducing modified calculation methods for handling unbalanced three-phase problems [4].

4.2.1 What is Clarke Transform?

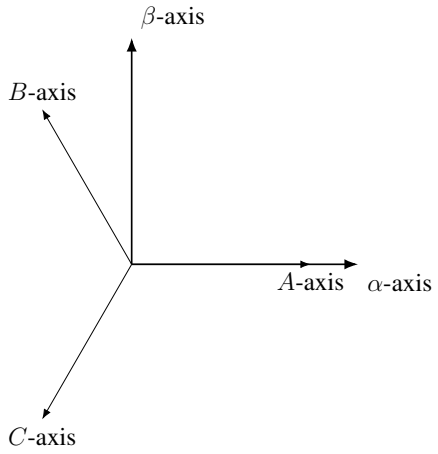


Figure 4.2: Clarke Frame of reference

E. Clarke developed the method for transforming stationary circuits into a stationary reference frame. In Clarke's transformation, the two-phase stationary variables are represented as α and β, with the α-axis and β-axis being orthogonal to each other [2].This transformation simplifies the analysis of three-phase electrical systems by projecting the original quantities onto a stationary reference frame. It decomposes the three-phase variables into two orthogonal components: alpha (α) and beta (β), which are aligned with the stationary reference axes, called the Clarke reference frame. The transform matrix is given by:

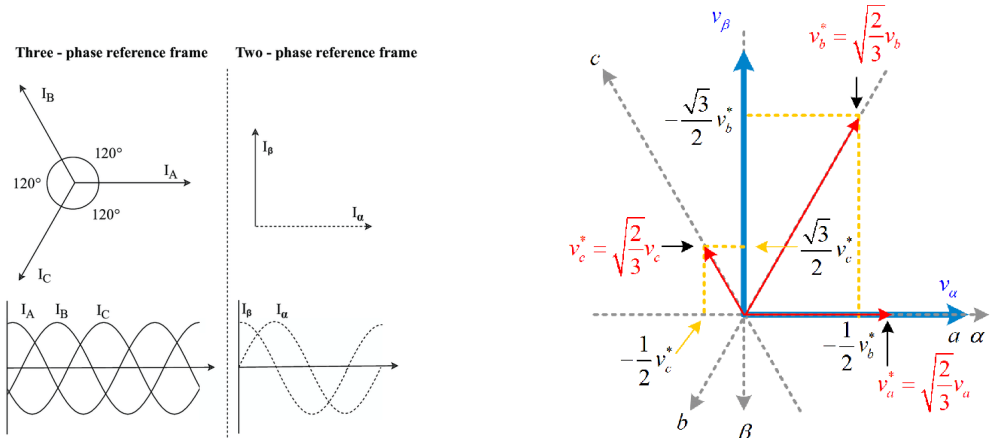
$$T_{\alpha\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix}$$

4.2.2 Derivation of the Clarke Transform Matrix

To derive the Clarke transformation, we resolve the three-phase quantities V_a, V_b, V_c along the α and β axes. The transformed quantities V_α and V_β are simplified according to Figure 4.3b. The normalization term $\frac{2}{3}$ ensures that the magnitudes of the quantities in the Clarke frame match those of the three-phase frame.

$$V_\alpha = \frac{2}{3}(V_a - \frac{1}{2}V_b - \frac{1}{2}V_c)$$

$$V_\beta = \frac{2}{3}(\frac{\sqrt{3}}{2}V_b - \frac{\sqrt{3}}{2}V_c)$$



(a) Clarke transformation

(b) Clarke transformation Derivation

Figure 4.3: Clarke transformation and its derivation

Converting this to matrix form, we get:

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

or we can write it as:

$$V_{\alpha\beta 0} = T_{\alpha\beta 0} V_{abc}$$

Where,

$$V_{\alpha\beta 0} = \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix}$$

$$V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$T_{\alpha\beta 0} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix}$$

For a balanced three-phase system where $V_a + V_b + V_c = 0$, the equations simplify to:

$$V_\alpha = V_a$$

$$V_\beta = \frac{2}{\sqrt{3}}(V_a + 2V_b)$$

$$V_0 = 0$$

4.3 Park transform

The Park transform, also known as the dq transformation, is another fundamental mathematical tool used in the analysis of three-phase electric machines.In the late 1920s, R.H. Park[3] introduced a new approach to electric machine analysis. He formulated a change

of variables which replaced variables such as voltages, currents, and flux linkages associated with fictitious windings rotating with the rotor. He referred the stator and rotor variables to a reference frame fixed on the rotor. From the rotor point of view, all the variables can be observed as constant values

4.3.1 What is Park Transform?

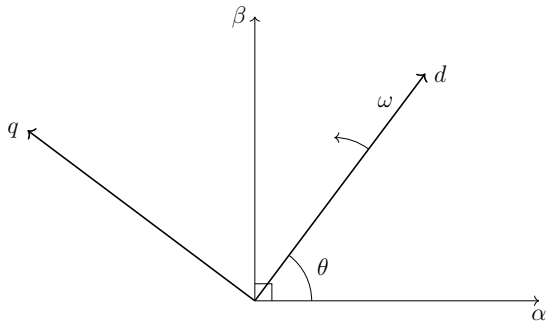


Figure 4.4: Park Frame of reference

The Park transform shifts the perspective from the traditional stationary reference frame to a rotating reference frame that moves with the rotor. This transformation effectively decouples the complex interactions between variables such as voltages, currents, and flux linkages that occur in three-phase systems. By aligning with the rotor's magnetic field, the transform separates these variables into two orthogonal components: d (direct) and q (quadrature). Figure:4.5

In practical terms, within the dq frame, d represents the component aligned with the rotor flux (direct axis), while q represents the component perpendicular to the rotor flux (quadrature axis). This separation facilitates independent control of the torque-producing and magnetizing currents in field-oriented control strategies, essential for optimizing the performance of electric machines.

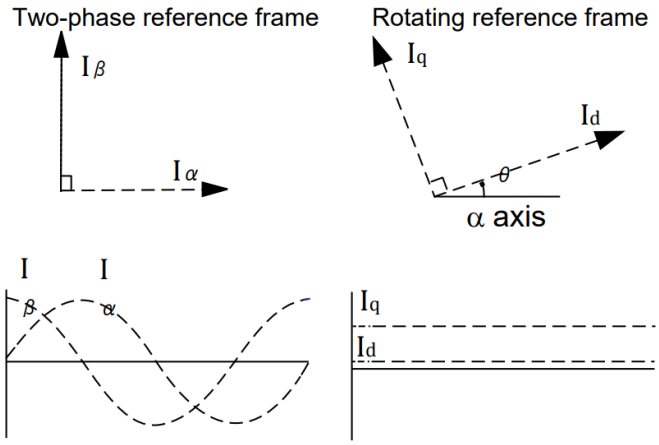


Figure 4.5: Park Transform

To derive the Park transformation matrix, we first define the transformation angle θ, which corresponds to the rotor angle. By applying an axis rotation and rotating the Clarke frame

by θ, we obtain the transformation matrix T_{dq0}.

$$T_{dq0} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

4.3.2 Derivation of the Park Transform Matrix

Where θ is the electrical angle of the rotor position. The Park transform equations for transforming the three-phase quantities V_α, V_β, V_0 to the dq frame are:

$$V_d = V_\alpha \cos\theta + V_\beta \sin\theta$$
$$V_q = -V_\alpha \sin\theta + V_\beta \cos\theta$$
$$V_0 = V_0$$

Converting these equations into matrix form, we get:

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix}$$

or in the shorthand notation:

$$V_{dq0} = T_{dq0} V_{\alpha\beta0}$$

Where:

$$V_{dq0} = \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$

$$V_{\alpha\beta0} = \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix}$$

$$T_{dq0} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

4.4 PID Controller

The Proportional Integral Derivative (PID) Controller[5] is the most widely used control technique in industry. The popularity of PID Controller because of their robust performance in a wide range of operating condition and its simple functionality. Industrial processes are subjected to variation in parameters and parameters perturbations.

4.4.1 What is PID Controller?

A PID Controller consists of a controlled system known as the Plant and a Controller designed to manage the overall system behavior. The transfer function of the PID Controller in the S-domain is given by:

$$K_p + \frac{K_i}{S} + K_d S$$

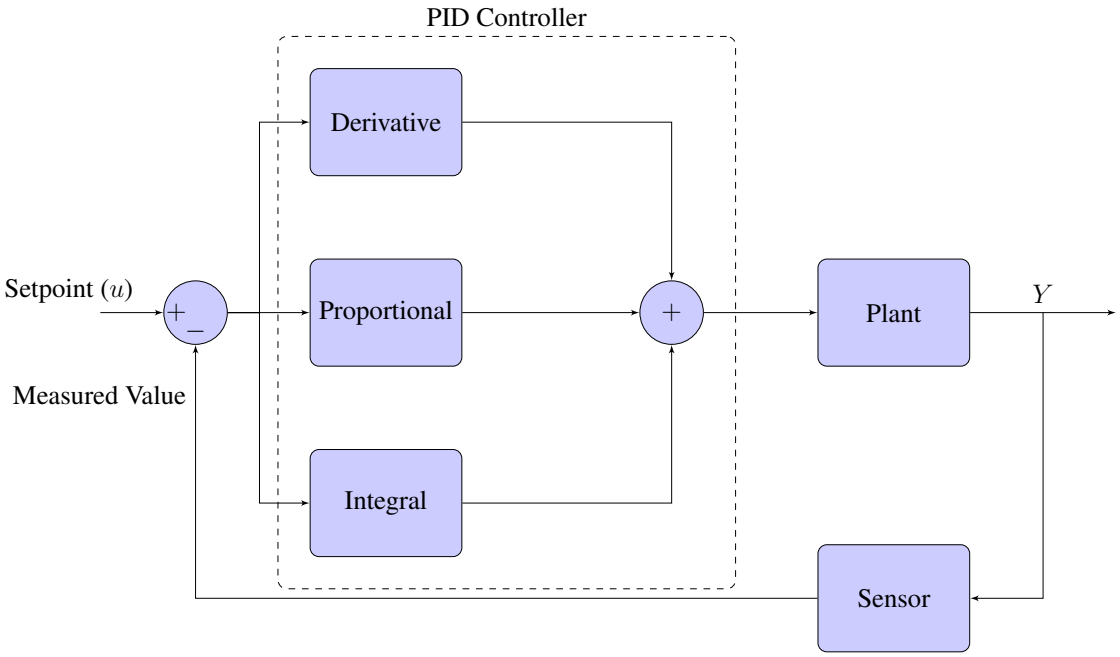


Figure 4.6: PID Controller Diagram.

Where K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain. The error (e) is the difference between the desired reference value (R) and the actual output (Y). The controller processes this error signal, computing its derivative and integral. The signal sent to the actuator (u) is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{de(t)}{dt}$$

This output signal (u) is sent to the plant, resulting in a new output (Y). This output is then fed back to compute a new error (e). The PID Controller continuously processes the new error signal, calculating its derivative and integral in an ongoing loop.

4.4.2 Feedforward Control

While PID controllers are effective at correcting errors based on feedback from the process variable (Process Variable), they can be enhanced by incorporating Feedforward Control. Feedforward Control is a proactive approach that anticipates disturbances and preemptively adjusts the controller output to minimize their effects on the Process Variable.

Why Use Feedforward Control?

In industrial processes, disturbances such as changes in feed flow rates, variations in raw material quality, or environmental factors can significantly impact the Process Variable. These disturbances are often unpredictable and can lead to deviations from the setpoint, requiring the PID controller to react and correct the error. However, by the time the disturbance affects the Process Variable, some amount of error may have already occurred.

Feedforward Control[6] addresses this issue by using a model or direct measurement of the disturbance to predict its effect on the Process Variable. This prediction is used to

generate a feedforward signal that is added to the PID controller's output. By doing so, the controller compensates for the disturbance before it affects the Process Variable, thereby reducing the error and improving the response time.

Types of Feedforward Control

There are two main types of Feedforward Control:

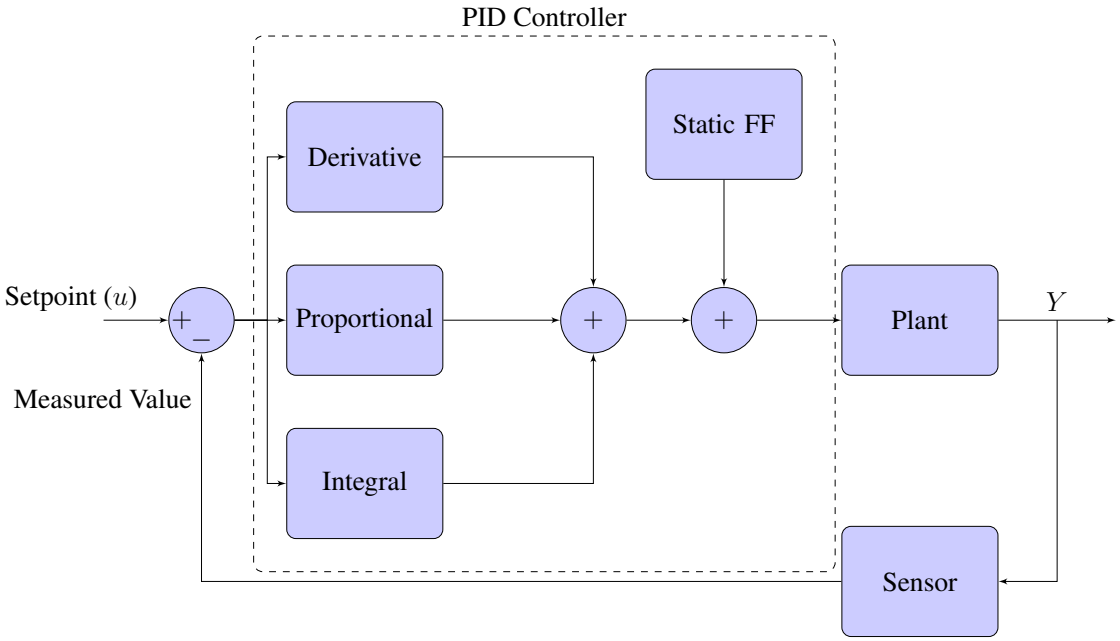


Figure 4.7: PID Controller and Static Feedforward Control.

1. **Static Feedforward Control**: This type calculates a steady-state gain based on the relationship between the disturbance variable and the Process Variable. The calculated gain is then added directly to the controller output. While effective for steady disturbances, it does not account for dynamic changes in the process.

2. **Dynamic Feedforward Control**: Dynamic Feedforward Control considers the dynamic response of the process to disturbances. It incorporates the time constant and dynamics of the disturbance to provide a more accurate compensation. This approach requires a model of the process dynamics or real-time measurement of the disturbance.

Benefits of Feedforward Control

- **Improved Disturbance Rejection**: By preemptively adjusting the controller output, Feedforward Control can significantly reduce deviations from the setpoint caused by disturbances.

- **Enhanced Stability**: Minimizing the impact of disturbances helps maintain stability in the control loop, reducing oscillations and improving overall system performance.

- **Efficiency**: Reducing the need for corrective action by the PID controller can extend equipment life and improve process efficiency.

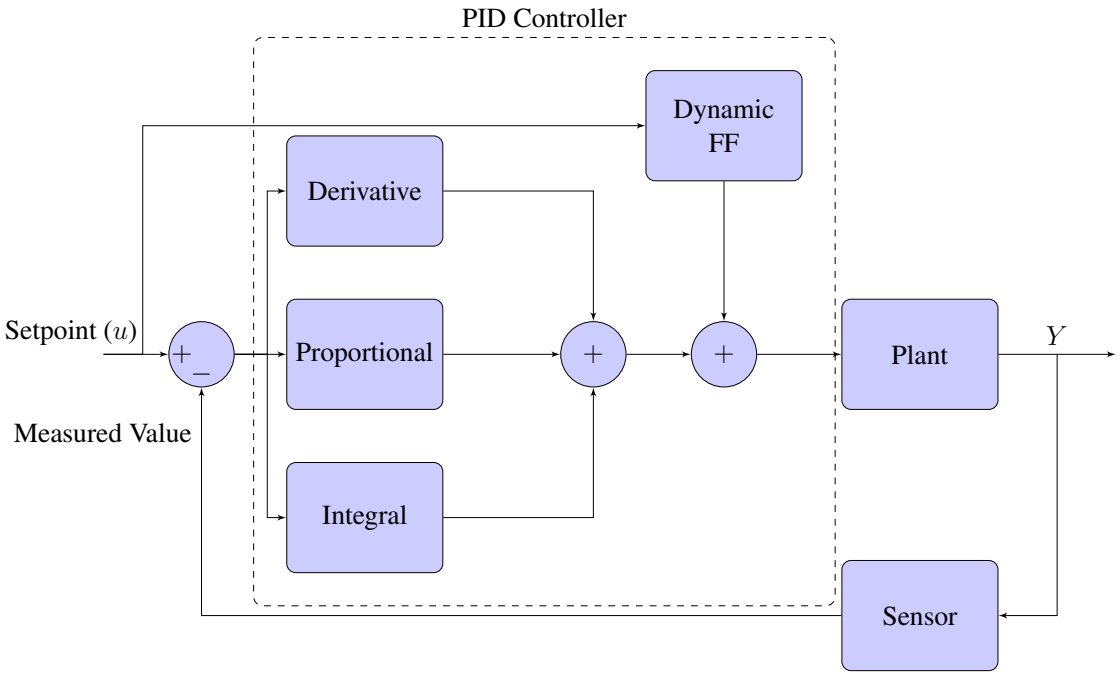


Figure 4.8: PID Controller and Dynamic Feedforward Control.

In conclusion, while PID controllers excel in maintaining setpoints based on feedback from the Process Variable, integrating Feedforward Control can enhance their performance by mitigating the effects of disturbances. By combining both feedback and feedforward strategies, industrial processes can achieve more robust and responsive control.

4.4.3 Zeigler-Nichols method

The Ziegler–Nichols tuning method is a heuristic method for tuning a PID controller, developed by John G. Ziegler and Nathaniel B. Nichols [7]. It involves setting the integral (T_i) and derivative (T_d) gains to zero and gradually increasing the proportional gain (K_p) until stable oscillations occur at the ultimate gain (K_u) and oscillation period (T_u). The parameters for different types of controllers are set based on these values, as shown in Table 4.1.

Table 4.1: Ziegler–Nichols Method Parameters for PID Controllers

Control Type	K_p	T_i	T_d	K_i	K_d
P	$0.5K_u$	-	-	-	-
PI	$0.45K_u$	$0.8\overline{3}T_u$	-	$0.54\frac{K_u}{T_u}$	-
PD	$0.8K_u$	-	$0.125T_u$	-	$0.10\frac{K_u}{T_u}$
Classic PID	$0.6K_u$	$0.5T_u$	$0.125T_u$	$1.2\frac{K_u}{T_u}$	$0.075\frac{K_u}{T_u}$
Pessen Integral Rule	$0.7K_u$	$0.4T_u$	$0.15T_u$	$1.75\frac{K_u}{T_u}$	$0.105\frac{K_u}{T_u}$
Some Overshoot	$0.3\overline{3}K_u$	$0.5T_u$	$0.3\overline{3}T_u$	$0.6\overline{6}\frac{K_u}{T_u}$	$0.1\overline{1}K_uT_u$
No Overshoot	$0.2K_u$	$0.5T_u$	$0.3\overline{3}T_u$	$0.4\frac{K_u}{T_u}$	$0.6\overline{6}K_uT_u$

The ultimate gain K_u is defined as $1/M$, where M is the amplitude ratio. The parameters K_i and K_d are derived from K_p, T_i, and T_d.

4.5 Phase Lock Loop (PLL)

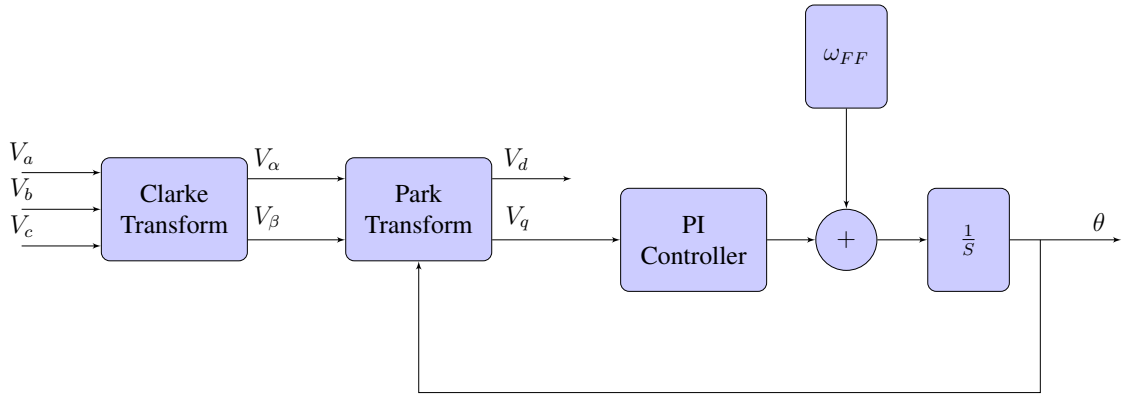


Figure 4.9: Three Phase PLL.

A phase-locked loop (PLL) is a nonlinear negative feedback control system designed to synchronize its output in both frequency and phase with an input signal. The concept of PLLs dates back to the 1930s when they were first used for the synchronous reception of radio signals. Over the years, PLLs have found applications in numerous fields, including the estimation of fundamental parameters (such as phase, frequency, and amplitude) of power signals, measurement of harmonics, interharmonics, and power quality indices, implementation of adaptive filters and robust controllers, and control of AC and DC machines. This section provides a detailed overview of the components and working of a three-phase PLL.

4.5.1 Working of Three-Phase PLL

Clarke Transformation

The working of a three-phase PLL begins with the input signals V_a, V_b, and V_c. These signals are first fed into the Clarke Transform, which converts them into two orthogonal components V_α and V_β in a stationary reference frame. The Clarke Transform simplifies the control and analysis of three-phase systems by reducing the three-phase signals into a two-dimensional plane.

Park Transformation

The next step involves the Park Transform, which converts the stationary reference frame components V_α and V_β into rotating reference frame components V_d and V_q. This transformation depends on an estimated phase angle θ generated by the integrator.

By transforming sinusoidal signals into DC signals, the Park Transform facilitates easier control of AC signals. It also allows the use of linear control methods like PID controllers to regulate the system, which would be more complex in the original AC signal domain.

PI Controller

The q-axis component V_q indicates the phase error between the input signal and the PLL output. If V_q is zero, the PLL is perfectly synchronized with the input signal. The V_q

component is fed into the PI (Proportional-Integral) Controller, which adjusts its output to minimize this error. The PI controller's output, combined with the feedforward frequency term ω_{FF}, is integrated to update the phase angle θ.

Integrator

The integrator ($\frac{1}{s}$) plays a crucial role by integrating the output of the PI controller to generate the estimated phase angle θ. This estimated phase angle is continuously fed back into the Park Transform to adjust the rotating reference frame. The feedback loop persists until the PLL output is perfectly synchronized with the input signal.

Summing Junction and Feedforward Path

To enhance the dynamic performance of the PLL, a feedforward term ω_{FF} is introduced. This term provides a reference frequency to assist the PLL in quickly adapting to changes in the input frequency. The summing junction combines the output of the PI controller and the feedforward path, ensuring coordinated feedback and feedforward control.

Output

The final output of the PLL is the estimated phase angle θ, which is crucial for synchronization purposes in various applications. This output can be utilized to synchronize other systems or for further control processes.
In summary, a three-phase PLL is an essential component in modern electrical and electronic systems, providing reliable synchronization and phase tracking capabilities for a wide range of applications.

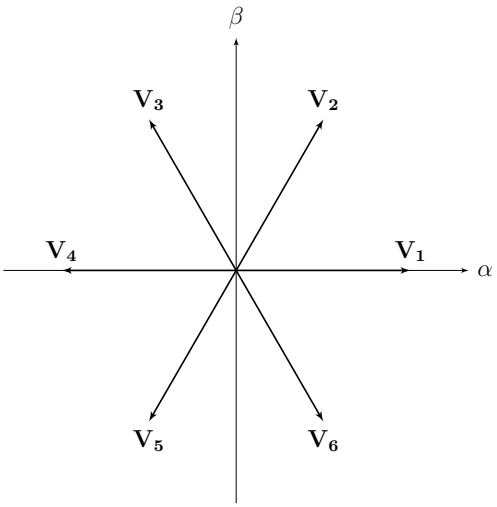
4.6 Space Vector Modulation

Space Vector Pulse Width Modulation (SVPWM) is a sophisticated modulation technique commonly used in three-phase inverters. It is designed to generate an output voltage waveform with precise control over both amplitude and frequency. SVPWM achieves this by synthesizing the output voltage using a combination of eight fundamental voltage vectors. These vectors include one "zero sequence vector," which represents a state where all three inverter legs are switched to the same state, and six "active vectors," which correspond to states where the inverter legs are switched to create specific voltage differences between the phases.

4.6.1 Basic Voltage Vectors

SVPWM utilizes eight basic voltage vectors, which are combinations of magnitudes and directions of the voltage vectors in the abc reference frame. These vectors are represented as V_0 through V_7 . Each vector corresponds to a unique combination of switching states for the three inverter legs (a, b, and c). Figure 4.10 outline these basic voltage vectors.

The vectors can be visualized in a hexagonal plane, where each active vector represents a specific direction and magnitude in the two-dimensional space of the voltage waveform. The zero vectors V_0 and V_7 do not contribute to the direction but help in controlling the



(a) Space Vector

Vector	S_A	S_B	S_C	Description
V_0	0	0	0	Zero Vector
V_1	1	0	0	Active Vector
V_2	1	1	0	Active Vector
V_3	0	1	0	Active Vector
V_4	0	1	1	Active Vector
V_5	0	0	1	Active Vector
V_6	1	0	1	Active Vector
V_7	1	1	1	Zero Vector

(b) Possible Switch States for the 8 Space Vectors

Figure 4.10: Space Vector and Switching States

overall voltage magnitude and maintaining the desired output voltage.

Each vector corresponds to specific switching states of the inverter's power transistors. The switching states determine which transistors are turned on and off, thereby controlling the flow of current in the three phases.

1. **Zero Vector (V_0 and V_7)**:These vectors represent a state where all three legs of the inverter are either connected to the positive or negative terminal of the DC bus, resulting in zero voltage output. These are used to control the overall magnitude of the output voltage and provide a zero voltage state during the modulation cycle.

2. **Active Vectors (V_1 to V_6)**:These vectors represent states where two legs are connected to one terminal of the DC bus and one leg to the other terminal. They define the direction and magnitude of the output voltage.

4.6.2 Vector Selection

Given the desired voltage vector in the $\alpha\beta$ plane, the nearest active vectors are selected to approximate it. This selection is based on the angle and magnitude of the desired vector relative to the active vectors. The process involves determining the sector in which the reference voltage vector lies. The $\alpha\beta$ plane is divided into six sectors, each spanning 60 degrees.

Once the sector is identified, the two adjacent active vectors defining this sector are selected. These vectors are chosen because they are the closest to the desired voltage vector and can best approximate its position. For example, if the desired voltage vector lies in the first sector, the active vectors V_1 and V_2 are selected. The reference vector is then synthesized by linearly combining these two active vectors and a zero vector.

The zero vectors (V_0 and V_7) are used to balance the time intervals to ensure that the total duration of each switching period is maintained. This selection and combination pro-

cess ensures that the resulting output voltage vector closely follows the desired reference vector, minimizing the error and improving the overall performance of the inverter.

4.6.3 Synthesis of Output Voltage

The output voltage synthesis entails selecting the nearest active vectors to achieve the desired voltage magnitude and phase angle. This is achieved by modulating between the closest two active vectors and incorporating a zero vector as needed.

Determining the Time Intervals

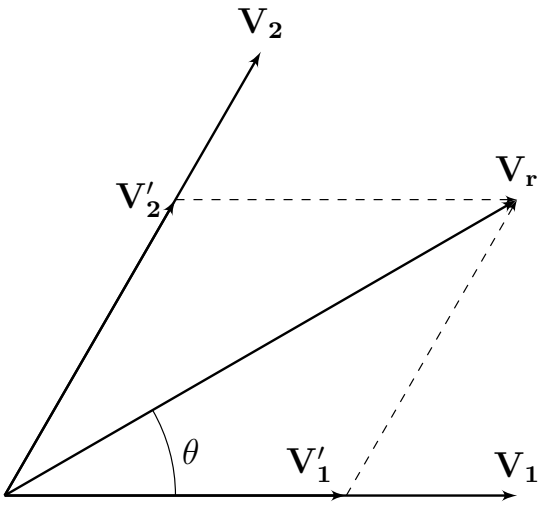


Figure 4.11: Time Interval Calculation

Given the vector V_r, represented by V_1 and V_2, the normalized time durations T_A and T_B are calculated as follows:

$$V_1' = V_1 \frac{T_A}{T_s}$$

$$V_2' = V_2 \frac{T_B}{T_s}$$

Using the sine law:

$$\frac{V_1'}{\sin\left(\frac{\pi}{3} - \theta\right)} = \frac{V_2'}{\sin\theta} = \frac{V_r}{\sin\frac{2\pi}{3}}$$

$$\frac{V_1 T_A}{\sin\left(\frac{\pi}{3} - \theta\right)} = \frac{V_2 T_B}{\sin\theta} = \frac{V_r T_s}{\sin\frac{2\pi}{3}}$$

$$T_A = \frac{V_r}{V_1}\frac{2}{\sqrt{3}} T_s \sin\left(\frac{\pi}{3} - \theta\right)$$

$$T_B = \frac{V_r}{V_2}\frac{2}{\sqrt{3}} T_s \sin\theta$$

Magnitude of $V_1 = V_2 = \frac{2}{3}V_D$
In normalized units, where $M = \frac{\sqrt{3}V_r T_s}{V_D}$:

$$T_A = M \sin\left(\frac{\pi}{3} - \theta\right)$$

$$T_B = M \sin \theta$$

M is the modulation index.
For the N-th Sector, $\theta \rightarrow \theta - (N-1)\frac{\pi}{3}$:

$$T_A = M \sin \left(\frac{N\pi}{3} - \theta \right)$$

$$T_B = M \sin \left(\left(-(N-1)\frac{\pi}{3} \right) + \theta \right)$$

Switching Sequence

Implementing a switching sequence that minimizes switching losses and ensures smooth transitions between vectors is crucial for the efficiency and performance of SVPWM. This sequence involves switching between the active and zero vectors in a manner that reduces the number of switching operations and distributes the switching events evenly across the phases.

The primary goal is to minimize the number of times the switches in the inverter change states, which helps in reducing switching losses. By doing so, the overall efficiency of the inverter improves, and the heat generated by switching operations is minimized. The secondary goal is to ensure that the transitions between the voltage vectors are smooth, which helps in maintaining a high-quality output voltage waveform with minimal harmonic distortion.

Sector	Sequence	Active Vector 1	Zero Vector	Active Vector 2
$0° - 60°$	Case 1	$V1$	$V0$	$V2$
$60° - 120°$	Case 2	$V2$	$V0$	$V3$
$120° - 180°$	Case 3	$V3$	$V0$	$V4$
$180° - 240°$	Case 4	$V4$	$V0$	$V5$
$240° - 300°$	Case 5	$V5$	$V0$	$V6$
$300° - 360°$	Case 6	$V6$	$V0$	$V1$

Table 4.2: Switching Sequence for Each Sector

Gate Pulse Generation

The gate pulses are generated in a specific manner to achieve these objectives. When the inverter bridge transitions through different active vectors, the switching sequence is designed such that only one of the half-bridges changes its state at any given time. This is achieved by arranging the active and zero vectors in a specific order, ensuring that the transitions involve only a single switch change per half-bridge.

To determine the optimal switching sequence, the following steps are taken:

- **Sector Division**:The entire space vector plane is divided into six sectors, each spanning 60 degrees. Each sector has a unique combination of active and zero vectors that are used to synthesize the desired output voltage vector.

- **Case Analysis for Each Sector**: For each of the six sectors, a detailed analysis is performed to arrange the active and zero vectors in an optimal sequence. This involves selecting the nearest active vectors to the desired output vector and arranging them along with the zero vectors in a way that minimizes switching operations.
- **Sequence Arrangement**:The active and zero vectors are arranged in a sequence that ensures only one of the half-bridges changes its state at any time. This typically involves transitioning from an active vector to a zero vector, then to the next active vector, and so on. The specific sequence depends on the position of the desired output vector within the sector.

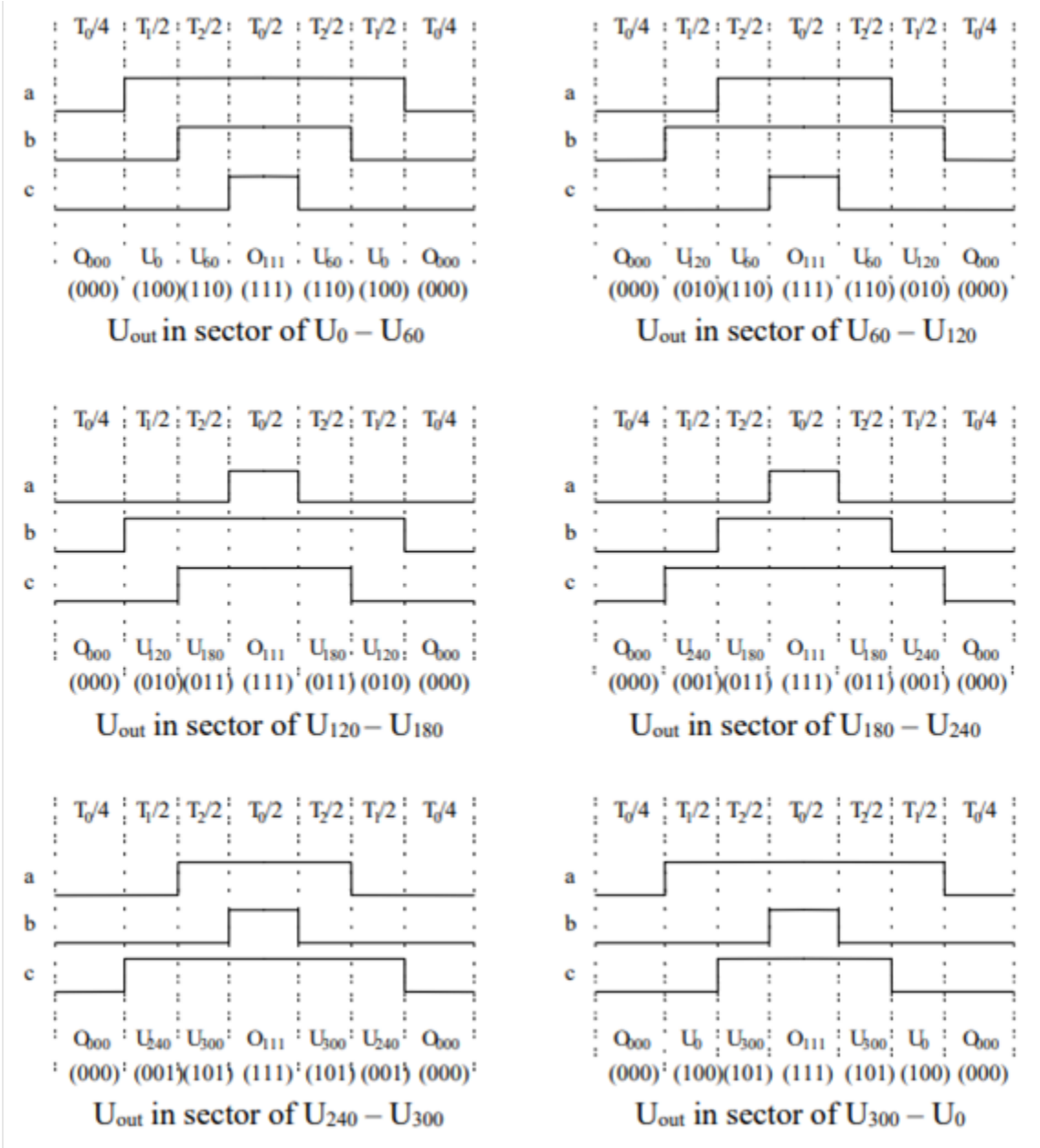


Figure 4.12: Gate Pulse Sequence

4.7 Matlab/SIMULINK Simulation

In this section, I will explain the setup-by-steo process I took for building and Active Front End (AFE) in SIMULINK/MATLAB. This involves creating a three-phase grid, making a three-phase bridge, implementing a line-tophase voltage conversion function, and developing a three-phase Phase-Locked-Loop(PLL) for grid sunchronization. I will also cover the park and clarke transformations, vector magnitude and angle calculation, current control, and gate time calculation.

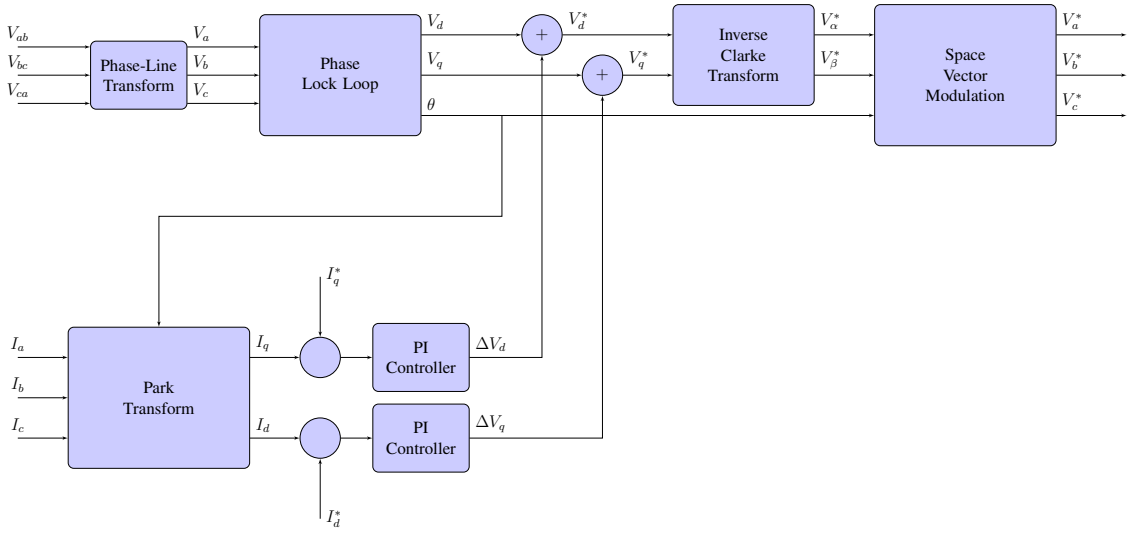


Figure 4.13: Active Front End Converter

4.7.1 Three-phase Grid

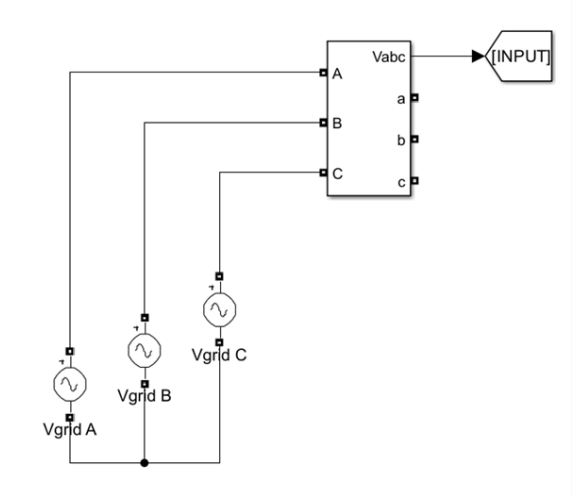


Figure 4.14: Three Phase Grid in SIMULINK

To begin, I created a three-phase grid using SIMULINK's AC source block. This grid represents the primary input power supply to the system. By connecting three AC source blocks in a star configuration, I established a three-phase AC source. Additionally, I

added a three-phase VI measurement block to accurately measure the grid voltage, which I labeled as $INPUT$ to maintain clarity within the simulation environment.

4.7.2 Three-Phase Bridge

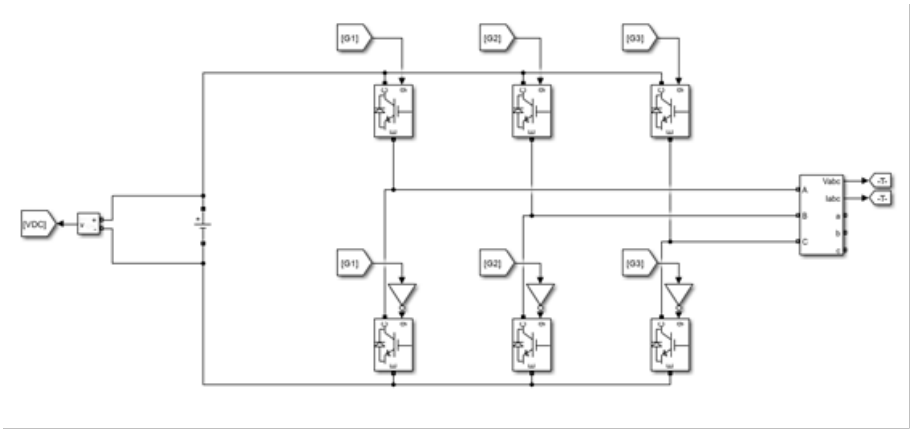


Figure 4.15: Front End Conveerter IGBT Bridge

To proceed, I constructed a three-phase bridge using Insulated Gate Bipolar Transistors (IGBTs) within SIMULINK. Each IGBT gate was labeled as G1, G2, and G3.

To power the bridge, a DC voltage source was added. This source provided the necessary voltage to drive the IGBTs and maintain stable operation of the bridge circuit. A voltage measurement block, labeled as VDC, was included to monitor the DC voltage across the bridge. This measurement block enabled real-time monitoring and adjustment of the DC voltage level during simulation.

For monitoring the output of the bridge, a three-phase VI measurement block was connected to the bridge's output terminals. This block facilitated the measurement and monitoring of both the output voltage (labeled as Vout) and current (labeled as Iout). These measurements were crucial for the control system to generate the necessary gate pulses for the IGBTs.

4.7.3 Line-To-Phase Voltage conversion

To apply control algorithms, I needed to convert the measured phase voltages to line voltages. This involves defining a transformation matrix and implementing it in a MATLAB function block.

```
function [Va, Vb, Vc] = lineToPhase(Vab, Vbc, Vca)
% Accepts three variables Vab, Vbc, and Vca representing phase
voltages

% Combine inputs into a matrix
V = [Vab, Vbc, Vca];

% Transformation matrix
T = [2/3, 1/3, 0;
     -1/3, -1/3, 0;
```

```
        -1/3, -2/3, 0];

    % Calculate phase voltages
    PhaseVoltages = T * V;

    % Extract individual phase voltages
    Va = PhaseVoltages(1);
    Vb = PhaseVoltages(2);
    Vc = PhaseVoltages(3);
    end
```

Listing 4.1: Phase to Line voltage transformation function

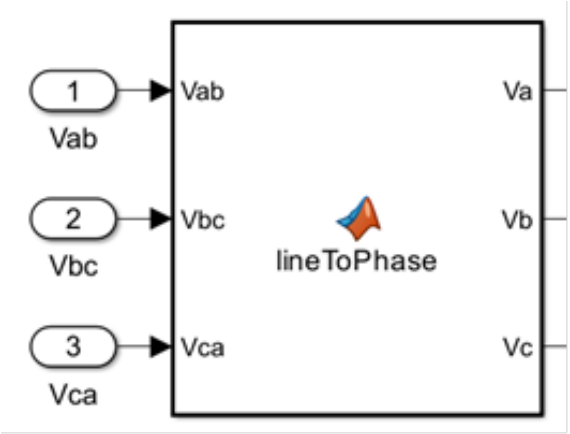


Figure 4.16: Phase-Line Voltage Conversion function

4.7.4 Three-Phase Phase-Locked Loop (PLL)

The PLL is crucial for accurately measuring the phase and frequency of the grid voltage, which is essential for generating constant voltages via the Park transformation. These voltages are subsequently used for current control within the Active Front End (AFE).

I implemented a MATLAB function block in SIMULINK to perform PLL operations. This function takes line voltages as inputs and outputs park voltages along with the phase angle (θ).

```
function [Vd, Vq, theta_o] = PLL(Va, Vb, Vc)
% Proportional and Integral Controller Parameters
kp = 28.935; % Proportional gain
ki = 173610; % Integral gain

% Sampling Time
dt = 1e-4; % Time step

% Persistent Variables Initialization
persistent theta; % Phase angle
if isempty(theta)
    theta = 0;
end

```

```
    persistent pid_i; % Integral term of PID controller
    if isempty(pid_i)
        pid_i = 0;
    end

    % Park Transformation Matrix
    phi = (2*pi)/3;
    T = [cos(theta), cos(theta - phi), cos(theta + phi);
         sin(theta), sin(theta - phi), sin(theta + phi)] * (2/3);

    % Input Vector
    Vabc = [Va; Vb; Vc];

    % Park Transformation
    ParkVoltages = T * Vabc;
    Vd = ParkVoltages(1);
    Vq = ParkVoltages(2);

    % Error Calculation
    error = Vq;

    % PID Controller
    pid_p = kp * error; % Proportional term
    pid_i = pid_i + ki * error * dt; % Integral term
    pid = pid_p + pid_i; % Total PID output

    % Frequency Calculation
    omega = 2*pi*50 + pid;

    % Phase Angle Integration
    theta = theta + (omega * dt);

    % Roll back to zero if theta exceeds 2*pi
    if theta > 2*pi
        theta = 0;
    end

    % Output the phase angle
    theta_o = theta;
end
```

Listing 4.2: Three-Phase Phase-Locked Loop

4.7.5 $DQ0 - \alpha\beta0$ Transformation

The newly calculated voltages V_d^* and V_q^* are derived from the output of the current PI loops. These voltages represent the transformed components in the stationary reference frame after applying the Inverse Clarke transform, which converts them from the rotating reference frame. This transformation is crucial for subsequent calculations, such as determining the timings required for space vector modulation.

In the provided MATLAB function block shown in Listing 4.3, the DQ-$\alpha\beta$ transformation is implemented using matrix operations.

```
    function [alpha, beta] = DQ_AlphaBeta(D, Q, angle)
```

```
    % Transformation Matrix
    T = [cos(angle), -sin(angle);
         sin(angle), cos(angle)];

    % Input Vector
    DQ = [D; Q];

    % AlphaBeta Transformation
    AlphaBeta = T * DQ;
    alpha = AlphaBeta(1);
    beta = AlphaBeta(2);
end
```

Listing 4.3: Three-Phase Phase-Locked Loop

4.7.6 Reference Signal Generator

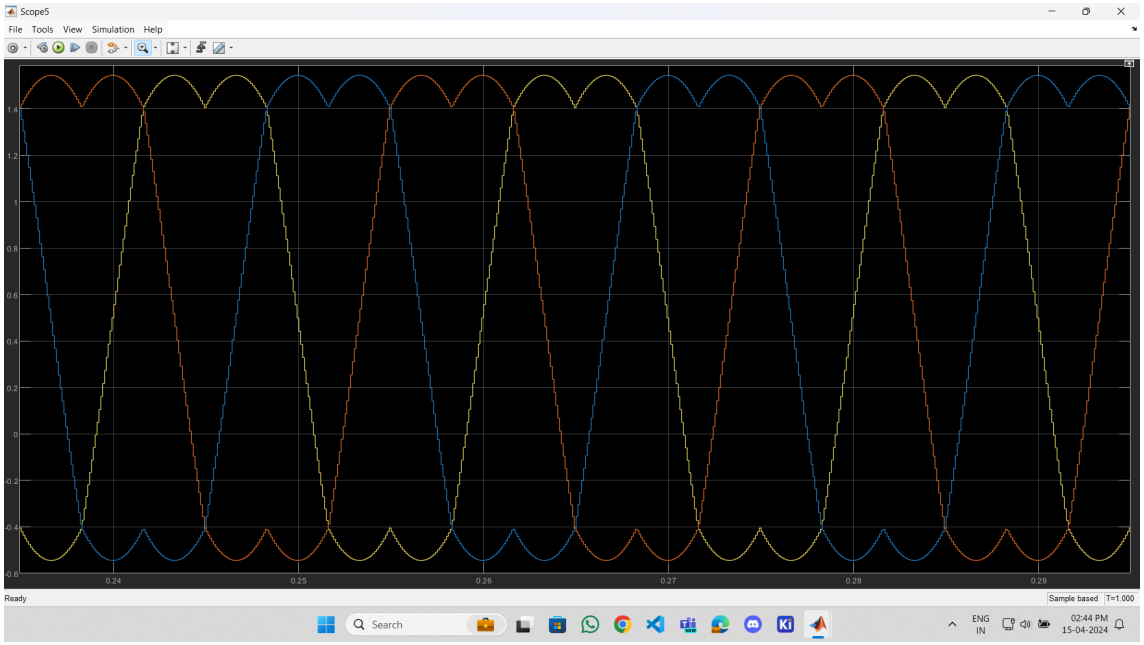


Figure 4.17: Space Vector Modulation

The Reference Signal Generator is responsible for generating the reference signals required for controlling the active front end. These signals, represented in the $\alpha\beta 0$ frame, are used to create space vector modulated signals for the three phases. These modulated signals are compared with a triangle wave to generate the PWM signal for controlling the IGBT.

Polar Voltage Conversion

The new Clarke voltages obtained from the inverse Clarke transform function are converted to polar voltages. The magnitude of the vector is calculated using the Pythagorean theorem:

$$V = \sqrt{\alpha^2 + \beta^2}$$

To calculate the vector angle, the ‘atan2‘ function is used because it provides angles within the range of -2π to 2π:

$$\theta = \text{atan2}(\alpha, \beta)$$

```
    V = sqrt(alpha^2 + beta^2);

    theta = atan2(alpha,beta);
    if theta < 0
        theta = theta + 2*pi;
    end
```

Listing 4.4: Polar Vector Calculation

Vector Time Calculation

Using the polar voltages derived from the inverse Clarke transform, the active vector timings and gate pulse timings are calculated using space vector modulation. The converter switches through vector states such that only one leg of the converter changes state at any given time.

```
    sector = ceil(6 * mod(\theta, 2\pi) / (2\pi));

    TA = V * sin(sector*pi/3 - \theta);
    TB = V * sin(-(sector-1)*pi/3 + \theta);
    T0 = 1 - TA - TB;

    switch sector
        case 1
            s1 = TA + TB + T0/2;
            s2 = TB + T0/2;
            s3 = T0/2;
        case 2
            s1 = TA + T0/2;
            s2 = TA + TB + T0/2;
            s3 = T0/2;
        case 3
            s1 = T0/2;
            s2 = TA + TB + T0/2;
            s3 = TB + T0/2;
        case 4
            s1 = T0/2;
            s2 = TA + T0/2;
            s3 = TA + TB + T0/2;
        case 5
            s1 = TB + T0/2;
            s2 = T0/2;
            s3 = TA + TB + T0/2;
        otherwise
            s1 = TA + TB + T0/2;
            s2 = T0/2;
            s3 = TB + T0/2;
    end
```

Listing 4.5: Vector Time Calculation

In Listing 4.5, the MATLAB function calculates the Switch timings $s1$, $s2$, and $s3$ based on the sector in which the angle θ falls. These timings are crucial for generating the gate

pulse signals that control the IGBTs in the active front end, ensuring proper modulation of the output voltage.

4.7.7 Current Controller

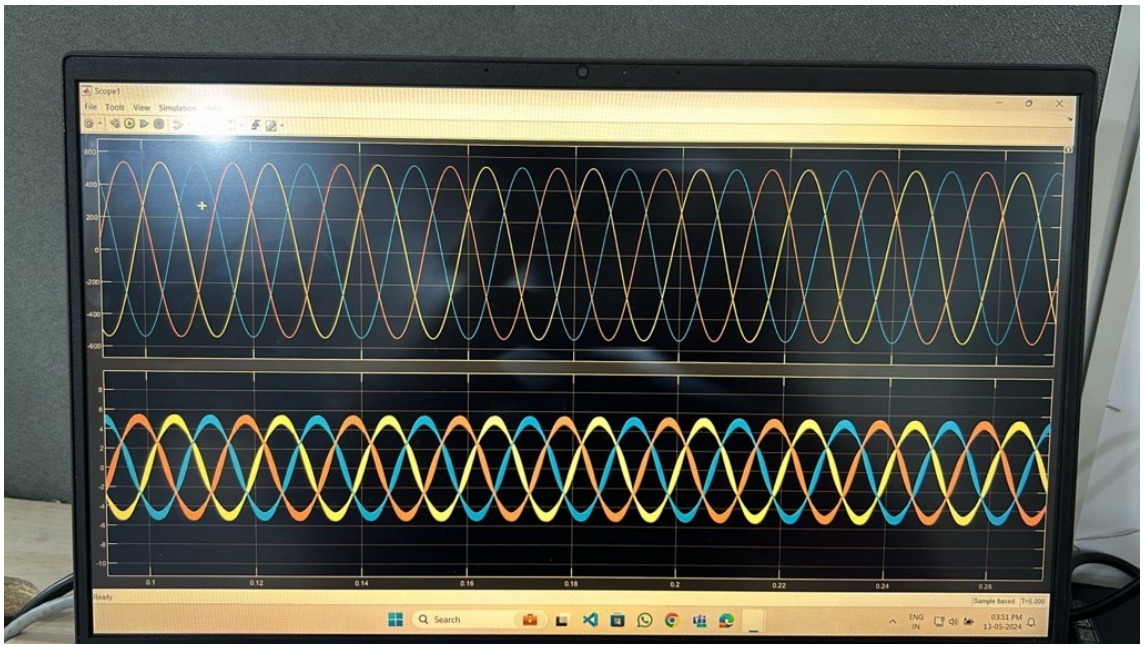


Figure 4.18: Closed Loop Simulation

The Current Controller plays a crucial role in regulating the output voltage to achieve precise current control. It operates by converting the line currents into the DQ-frame of reference and then feeding these components into a PI controller.

Park Transformation Function

The Park transformation function, as shown in Listing 4.6, converts the three-phase currents I_a, I_b, I_c into the DQ-frame of reference. This transformation aligns the current components I_d (direct axis) and I_q (quadrature axis) with the rotating reference frame, which is defined by the angle θ obtained from the voltage Phase-Locked Loop (PLL). This alignment ensures that the current remains in phase with the voltage, thereby achieving a unity power factor.

```
function [iq, id] = current_transform(ia, ib, ic, theta)
    % Input Vector
    Iabc = [ia; ib; ic];

    % Transformation Matrix
    T = (2/3) * [cos(theta), cos(theta - (2*pi)/3), cos(theta + (2*pi)
    /3);
                 sin(theta), sin(theta - (2*pi)/3), sin(theta + (2*pi)
    /3)];

    % Park Transformation
    Idq = T * Iabc;
    id = Idq(1);
    iq = Idq(2);
```

```
end
```

Listing 4.6: Park Transformation

PI Controller

The PI Controller, depicted in Listing 4.7, operates based on the I_q component derived from the Park transformation. It adjusts the demand V_d based on the error between the desired I_q setpoint and the actual I_q current. This control loop maintains precise current levels.

```
function Vd_demand = PI_Controller_q(iq, iq_set)
    dt = 1e-4;

    persistent pid_i; % Integral term of PID controller
    if isempty(pid_i)
        pid_i = 0;
    end

    % Proportional and Integral Controller Parameters
    kp = 47.25; % Proportional gain
    ki = 17010; % Integral gain

    % Error Calculation
    error = iq_set - iq;

    % PID Controller
    pid_p = kp * error; % Proportional term
    pid_i = pid_i + ki * error * dt; % Integral term
    pid = pid_p + pid_i; % Total PID output

    Vd_demand = pid;
end
```

Listing 4.7: PI Controller

These components work in tandem to ensure that the current is precisely controlled, aligning with the voltage phase to maintain optimal performance and power efficiency in the active front end.

5. Conclusion and Future scope

5.1 Conclusion

Throughout my internship at Statcon Electronics India Ltd., I gained extensive knowledge and practical experience in implementing Space Vector Pulse Width Modulation (SVPWM). This journey involved understanding and applying various mathematical transformations, developing control algorithms, and transitioning from simulation to real hardware implementation.
SVPWM offers several advantages over conventional techniques, such as:

- **Higher Efficiency**: SVPWM maximizes the DC bus voltage utilization, leading to improved efficiency in inverter operation. This is crucial for applications where energy efficiency is paramount, such as in renewable energy systems and electric vehicles.
- **Reduced Harmonic Distortion**: By optimizing the switching sequences, SVPWM reduces the harmonic distortion in the output waveforms. This results in cleaner and more stable power delivery, which is essential for sensitive electronic equipment and improving the overall power quality.
- **Improved Power Factor**: SVPWM enables better control over the output voltage and current, contributing to an improved power factor. This is beneficial in reducing energy losses and ensuring that power systems operate closer to their maximum efficiency.

Moreover, the hands-on experience with simulation tools like MATLAB/Simulink and practical implementation using STM32F411 microcontrollers has enriched my understanding of both software and hardware aspects of power electronics. This dual exposure has equipped me with a holistic view of the challenges and solutions in modern inverter technology.

5.2 Future Scope

The knowledge and skills developed during this internship have broad applications in various fields, including:

- **Hybrid Inverters**: Enhancing the efficiency and performance of hybrid inverters. By integrating SVPWM, hybrid inverters can achieve better efficiency and reliability, making them more viable for both residential and commercial energy solutions.

- **Active Front Ends**: Driving DC series motors in trains for power factor correction and voltage regulation. Implementing SVPWM in active front-end converters can lead to significant improvements in power quality and energy savings in traction systems.
- **Battery Charging**: Implementing SVPWM for efficient battery charging systems. With the growing demand for electric vehicles and renewable energy storage, efficient battery charging solutions are critical. SVPWM can contribute to faster and more efficient charging cycles, prolonging battery life and enhancing performance.
- **Electric Vehicle (EV) Drive Systems**: Applying SVPWM in EV drive systems to improve motor efficiency and reduce energy consumption. This can lead to extended range and better performance of electric vehicles, making them more competitive with traditional internal combustion engine vehicles.

Overall, this internship has been a valuable learning experience, providing me with the technical expertise and practical skills needed to contribute effectively to the field of power electronics and embedded systems. The insights gained have not only broadened my knowledge base but also ignited a passion for further exploration and innovation in this dynamic and impactful field.

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