Project Report

(Internship Semester January–June)

Design of LLC Based Resonant Converters

Submitted by

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Under the Guidance of

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Declaration

I hereby declare that the project work entitled "Design of LLC Converter" 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.Tech. Electronics and Communication Engineering, Punjab Engineering College (Deemed to be University), Chandigarh, under the guidance of Mr. Sarv Parteek Singh and Assistant Professor Muzaffar Imam, during January to June, 2024.

Date: July 8, 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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Acknowledgement

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Furthermore, I would like to express my sincere appreciation to Mr. Joysingha Paul for his invaluable guidance in the development of the LLC Converter and his assistance with LtSpice. 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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Contents

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 systems. During my internship at Statcon Electronics India Ltd, Noida, I was first assigned to explore LLC Converters and then make a simulation for the various circuits in the exisiting converters using LtSpice. I was part of the Hardware Design team and my task was to develop a LLC Resonant Converter according to the required specifications.

The aim of the project was to design a LLC Resonant converter for an IPS (Integrated Power Supply) for railways, providing efficienct power while reducing harmonic distortions and improving the power factor.

1.1 Timeline

My internship at Statcon Electronics India Ltd started on 2nd January, 2024. My mentor gave me the task of exploring LLC Converters and developing such converter as per the given specifications. This timeline will briefly explain the course of my internship from beginning to end.

1.1.1 January

In January, I started learning about LLC Converters and simulating control circuits in LtSpice. This involved understanding the basics of Switching Mode Power Supplies (SMPS), LC tank circuits, LLC topology for SMPS, etc. This exploration gave me a better grasp of how an LLC resonant converter works and its uses in power supplies.

1.1.2 Feburary

During February, I immersed myself in the study and testing of the exisiting LLC converter deeply understanding the working of the converter in much more detail and what all factors need to be taken care of when we design such a power supply. The work that I did included study of LLC converters, preparing (such as soldering the components etc.) the controller boards, finding and fixing the bugs that were arising in the hardware (such as issue of noise in feedback signals etc.).

1.1.3 March

During March, apart from the ongoing work in the testing of the motherboard and control circuit (which included hardware testing as well as software simulations in LtSpice and a comparitive analysis between them), I worked on developing the testing jig for the LLC converter which would be used when the converter is put into production in the company.

1.1.4 April

In April, I was provided the document of the current design of the LLC converter (how the converter is designed). I was asked to study the document and then carry out similar calculations for other specifications of the LLC converter.

1.1.5 May

In May, I found the methodoly of the design to be sub-optimal and then I did my own research, reading some research papers for design of an LLC Resonant Converter and completely made a new methodology for the design of the converter. I then calculated the values of the components using my methodology.

1.1.6 June

In June, I was asked to recalculate the values for the current converter in testing as well. I also noticed thar the transformer that they are using was sub-optimal as well and suggested a different core which satisfied all of the required parameters. I also worked on the PCB design of another project as well. I used Altium Designer for same.

2. Introduction

2.1 Problem Statement

My team at Statcon Electronics India Ltd has been focusing on enhancing the efficiency and performance of Switched Mode Power Supplies. Presently, most SMPS utilize switching of MOSFETs at high frequencies to generate an alternating high frequency signal which is then passed through a rectifier and filtered using capacitors. We use LLC Based Resonant Converters which have higher efficiency, and lower output voltage ripple than traditional SMPS. The aim of this project is to understand the working of such a converter and design one as well

2.2 Overview

2.2.1 LLC Converter

Figure 2.1 is a schematic of a basic LLC converter. The LLC has the following components:

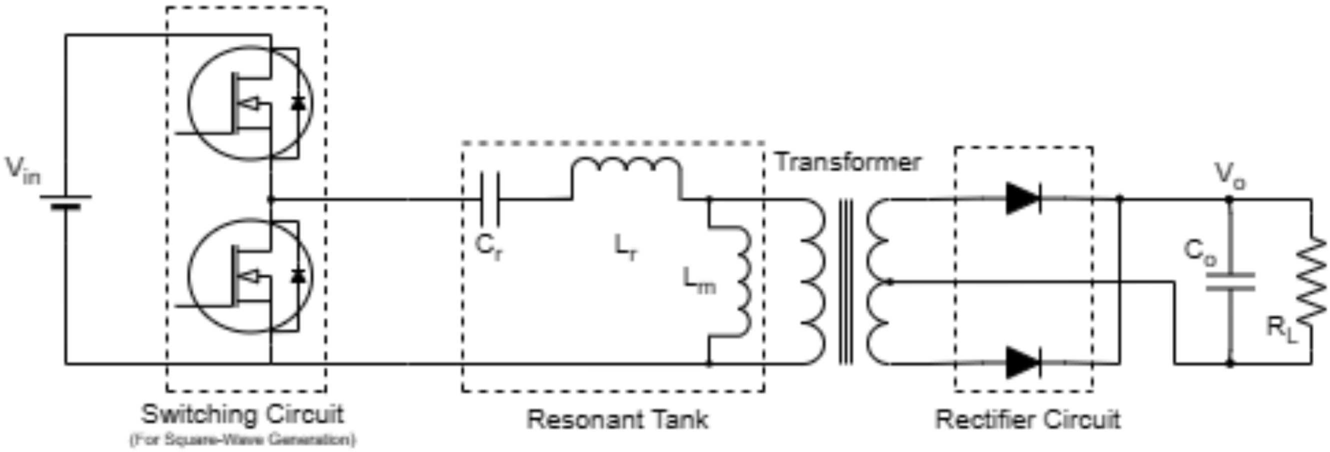


Figure 2.1: Diagram of an LLC based resonant converter

Switching Circuit

The switching circuit alternately switches the MOSFETs ON and OFF (full-bridge or half-bridge), generating a sort of square wave after the switching circuit, and before the resonant tank circuit.

Resonant Tank

The resonant tank circuit filters the higher-order harmonics and generates a sinusoidal signal of the fundamental frequency of the tank circuit to be fed into the primary side of the transformer.

Rectifier Circuit

A bridge rectifier (full-bridge or half-bridge) followed by the output capacitor rectifies the alternating voltage produced at the transformer and converts it into stable DC voltage.

2.3 Challenges

The challenges I faced in simulating and designing a LLC Based Resonant converter include:

- **Modeling the LLC converter**: Understanding the complex interactions between the switching circuit, resonant tank, and rectifier circuit and accurately modeling their behavior in simulation.
- **Component selection**: Choosing the appropriate resonant tank components to ensure optimal performance and efficiency.
- **Efficiency optimization**: Optimizing the converter design to maximize efficiency and minimize power losses.
- **Cost considerations**: Balancing the performance requirements with cost constraints to design a converter that is both efficient and cost-effective.
- **Validation and testing**: Verifying the performance of the designed converter through simulation and experimental testing to ensure it meets the desired specifications.

3. Work

3.1 Simulation

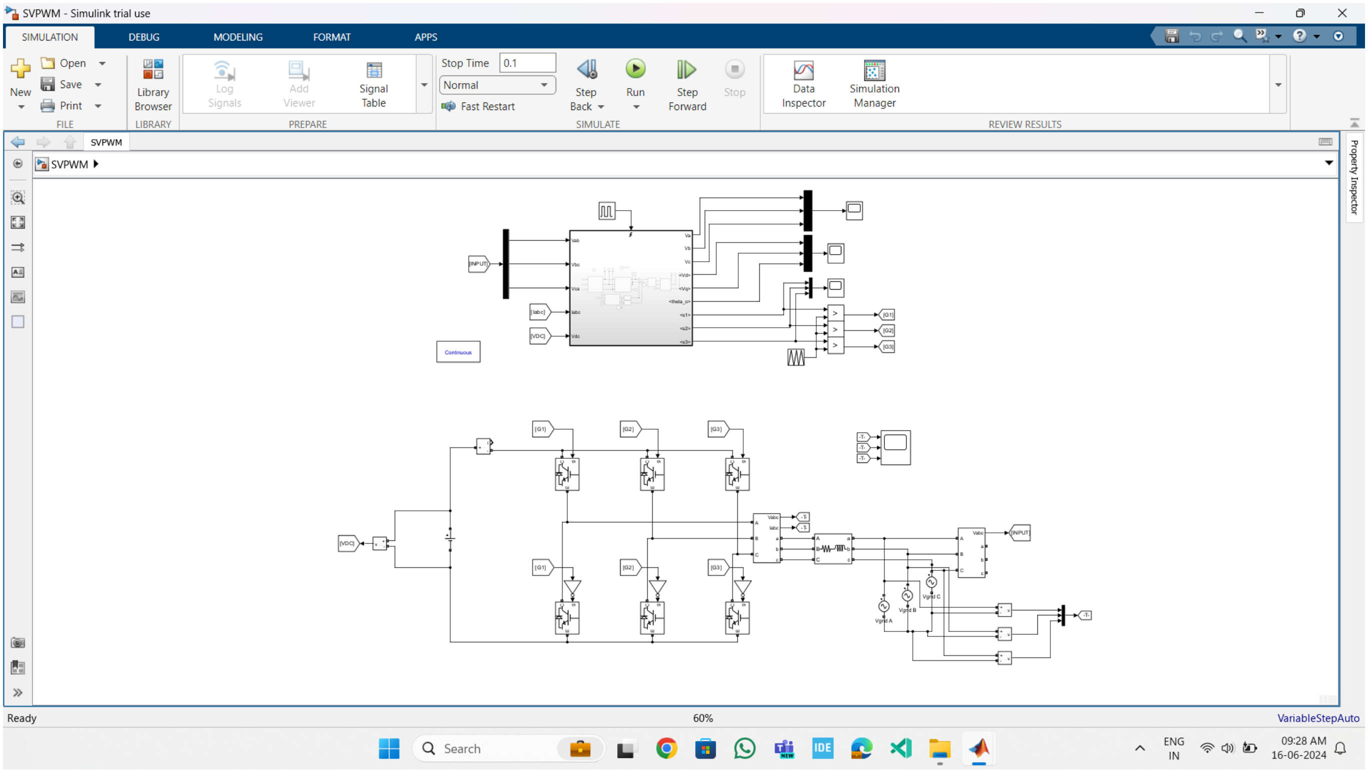


Figure 3.1: Simulation

Before initiating the design phase, it was imperative to conduct a comprehensive simulation of the existing design using LtSpice. The simulation setup involved creating the circuits for each individual sub-sections of the circuit and understanding as well as analyzing the behavior of each and every sub-circuit.

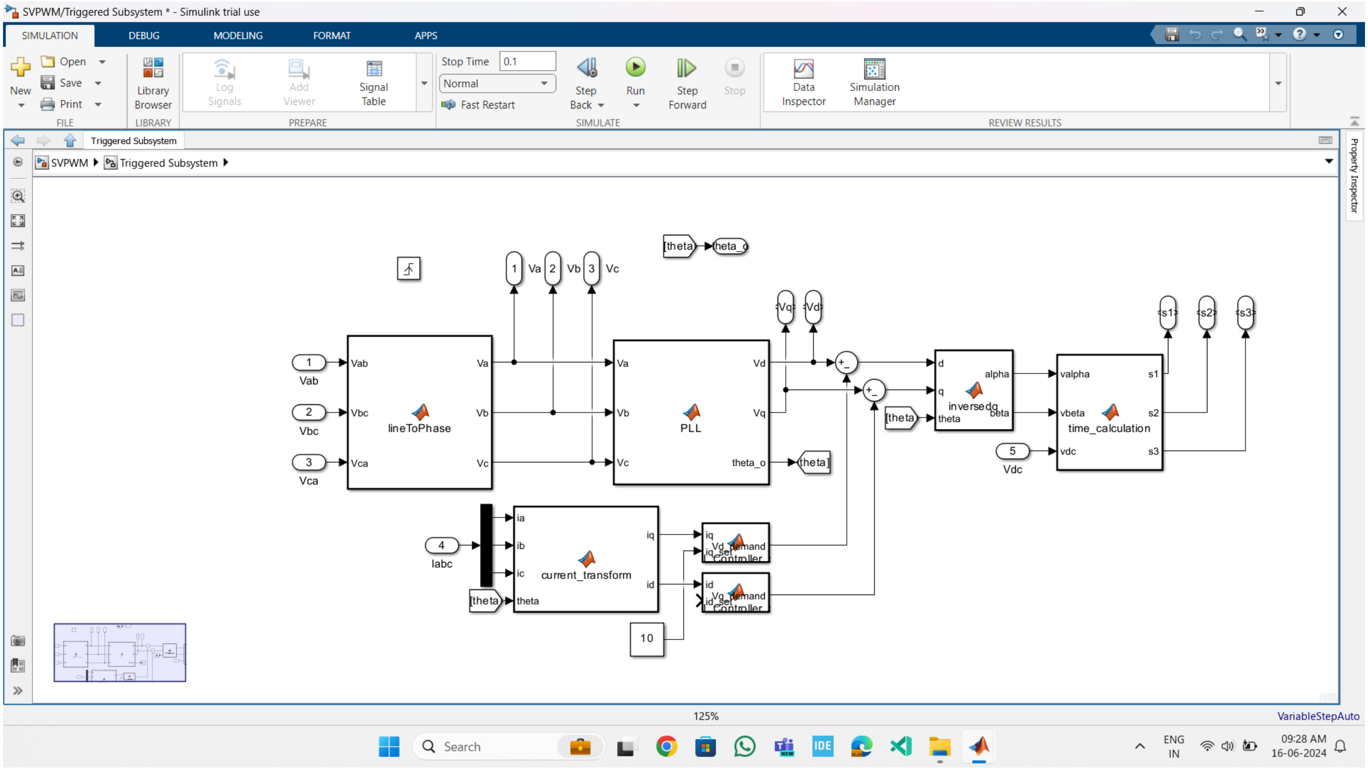


Figure 3.2: Control System

3.1.1 MATLAB Function Blocks in Simulation

3.1.2 Control System

Voltage Transformation

Phase-Locked Loop (PLL)

Current Measurement and Transformation

Current Regulation

Voltage Calculation and Transformation

Gate Timing Calculation

3.1.3 Power System

Three-Phase AC Source

Three-Phase IGBT Bridge

3.2 Testing

3.2.1 Microcontroller Selection

3.2.2 Implementation of Voltage transform functions

3.2.3 Microcontroller Programming and Testing

- **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.

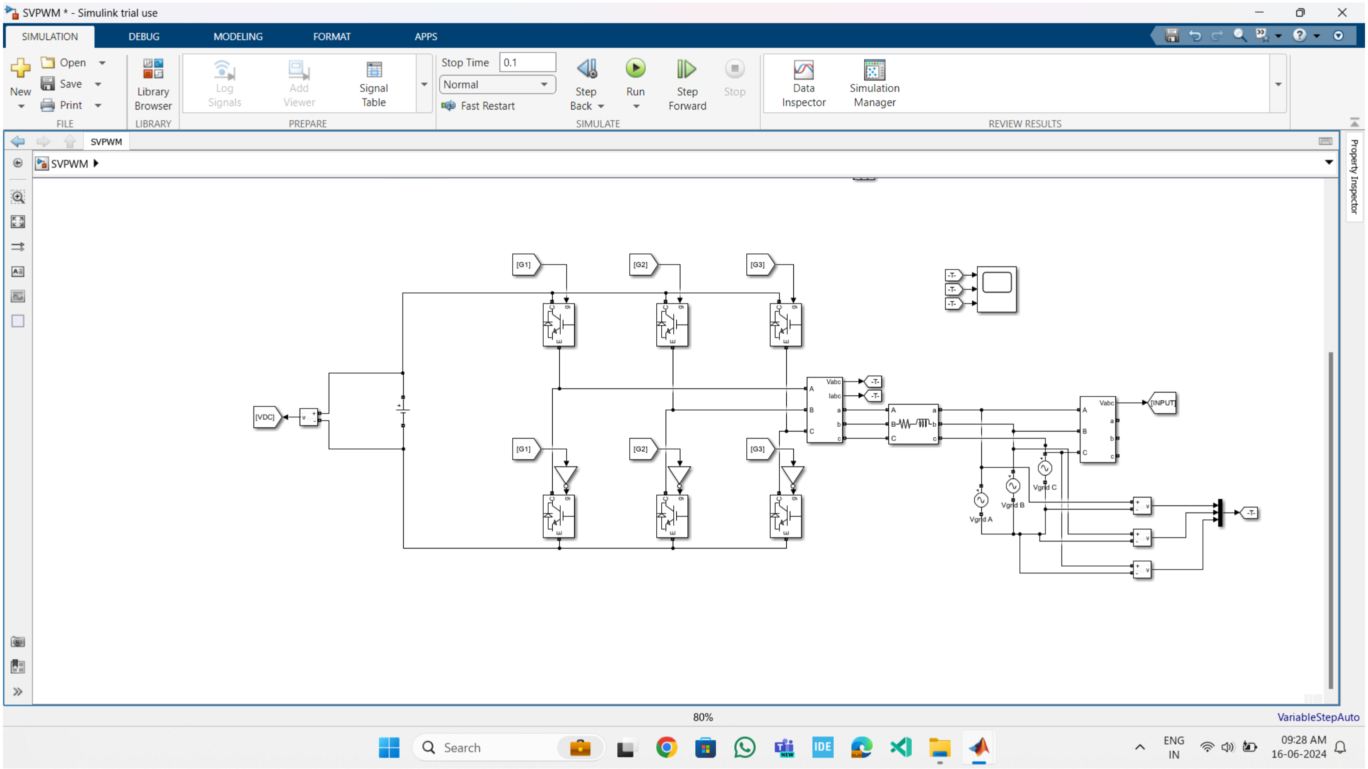


Figure 3.3: Power System

- **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).

3.3 Calculation of LLC values

3.3.1 MATLAB Function Blocks in Simulation

3.3.2 Control System

4. Review

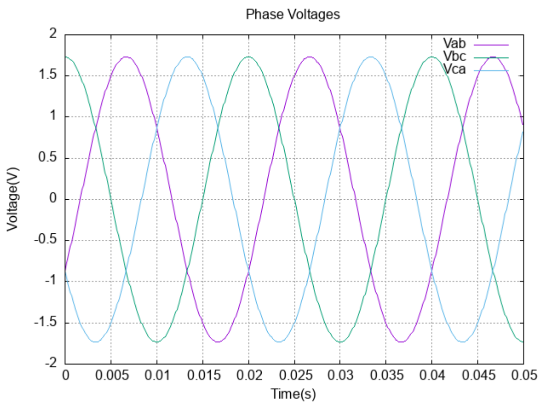
4.1 Company review

4.2 Project review

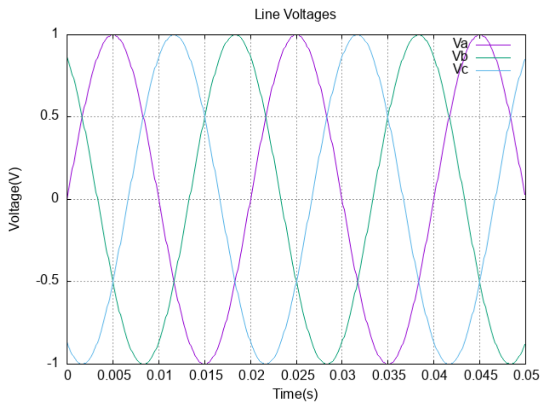
5. Details of work

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 desing of a LLC Resonant Converter.

5.1 Phase-Line Transformation



(a) Phase Voltages



(b) Line Voltages

5.1.1 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.

5.1.2 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.

5.1.3 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.

5.1.4 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:

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

5.2 Clarke transform

5.2.1 What is Clarke Transform?

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

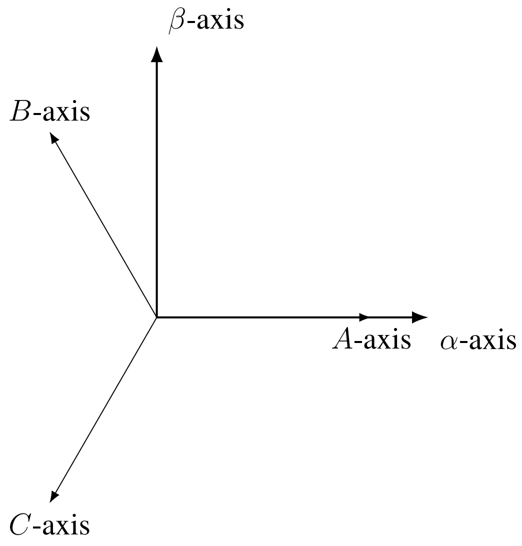
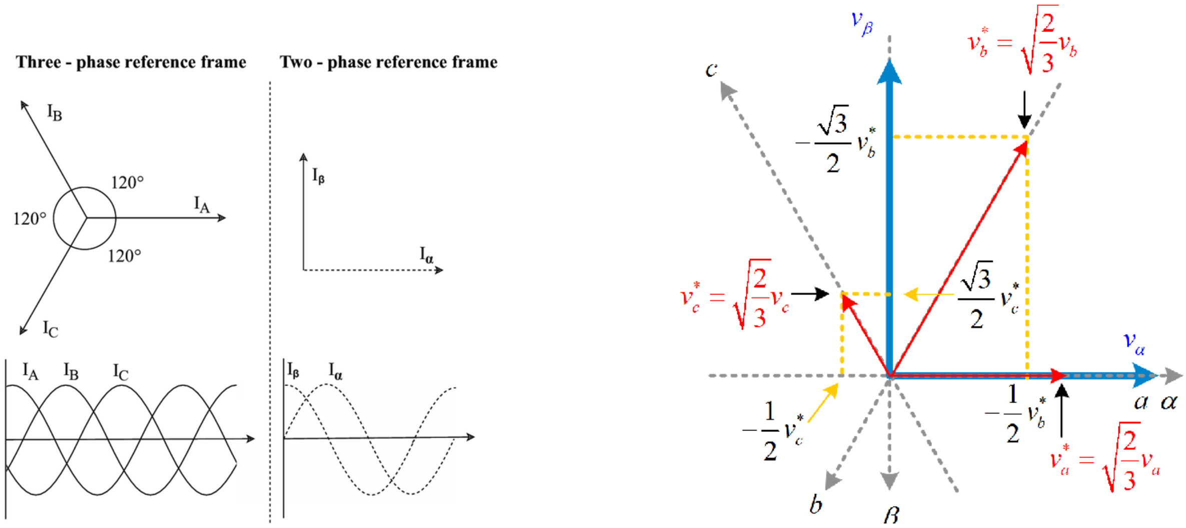


Figure 5.2: Clarke Frame of reference



(a) Clarke transformation

(b) Clarke transformation Derivation

Figure 5.3: Clarke transformation and its derivation

5.2.2 Derivation of the Clarke Transform Matrix

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

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

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,

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

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

$$T_{\alpha\beta0} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix}$$

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

$$V_\alpha = V_a$$

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

$$V_0 = 0$$

5.3 Park transform

5.3.1 What is Park Transform?

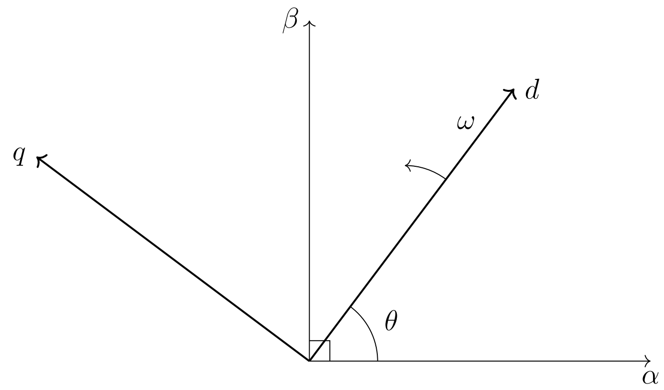


Figure 5.4: Park Frame of reference

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.

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}.

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

5.3.2 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:

$$V_d = V_\alpha \cos\theta + V_\beta \sin\theta$$

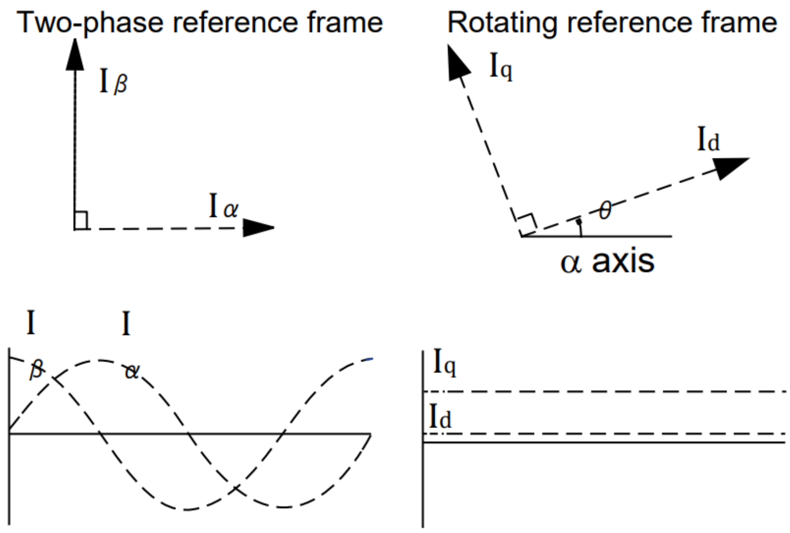


Figure 5.5: Park Transform

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

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:

$$V_{dq0} = T_{dq0} V_{\alpha\beta 0}$$

Where:

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

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

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

5.4 PID Controller

5.4.1 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:

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

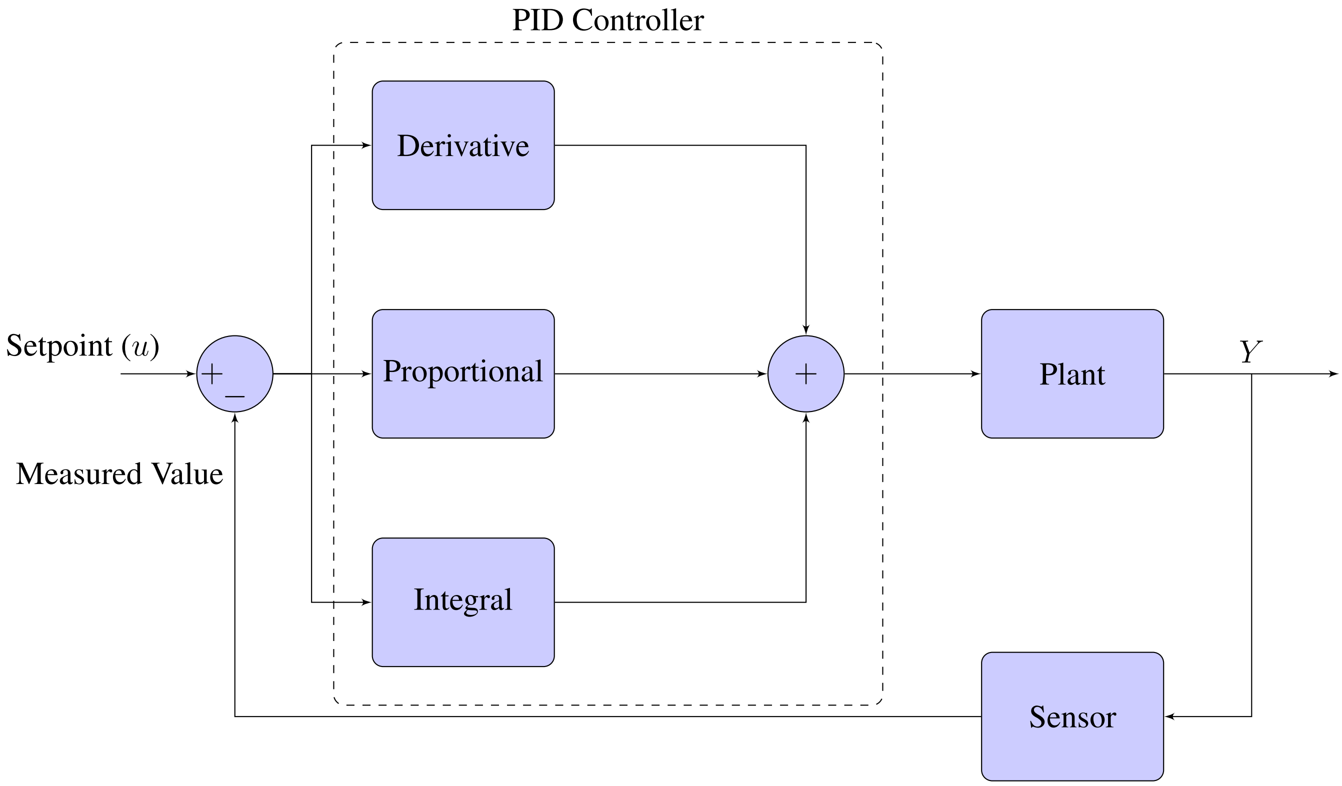


Figure 5.6: PID Controller Diagram.

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.

5.4.2 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 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:

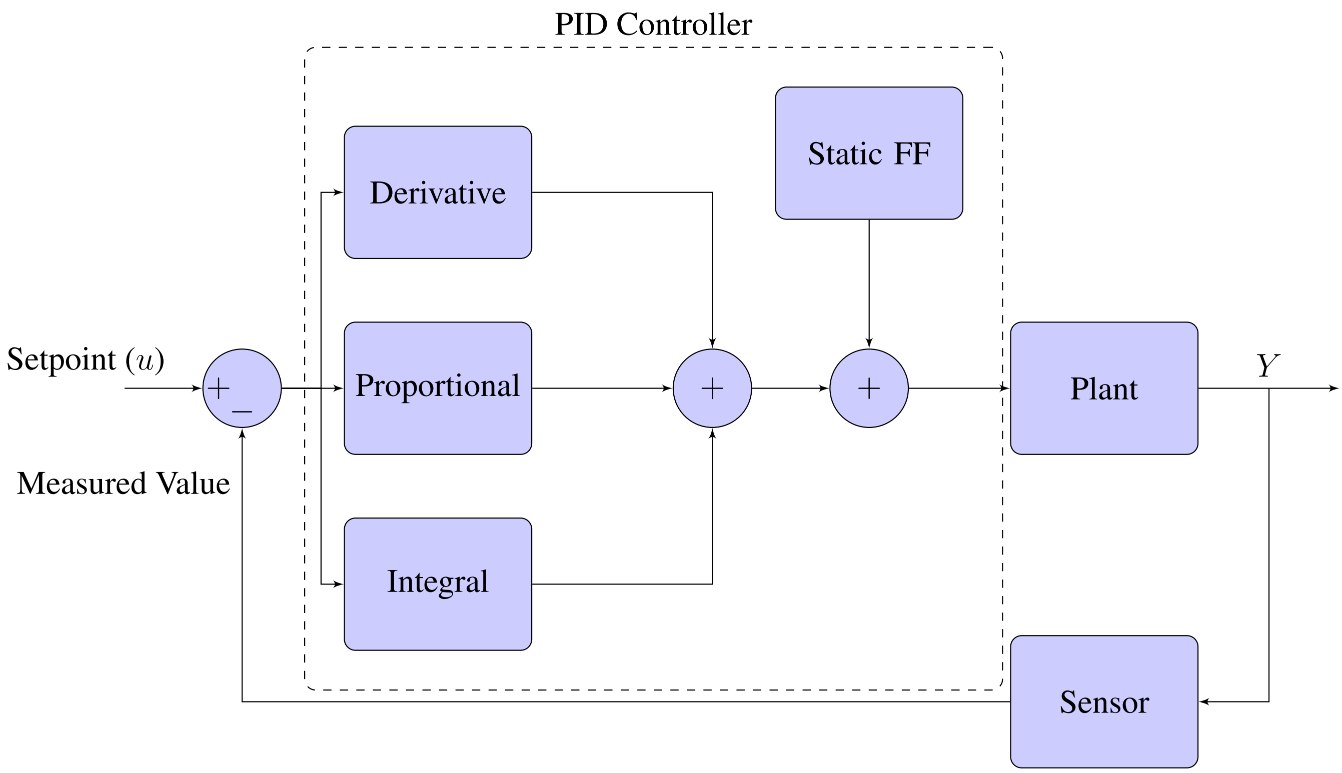


Figure 5.7: PID Controller and Static Feedforward Control.

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.

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.

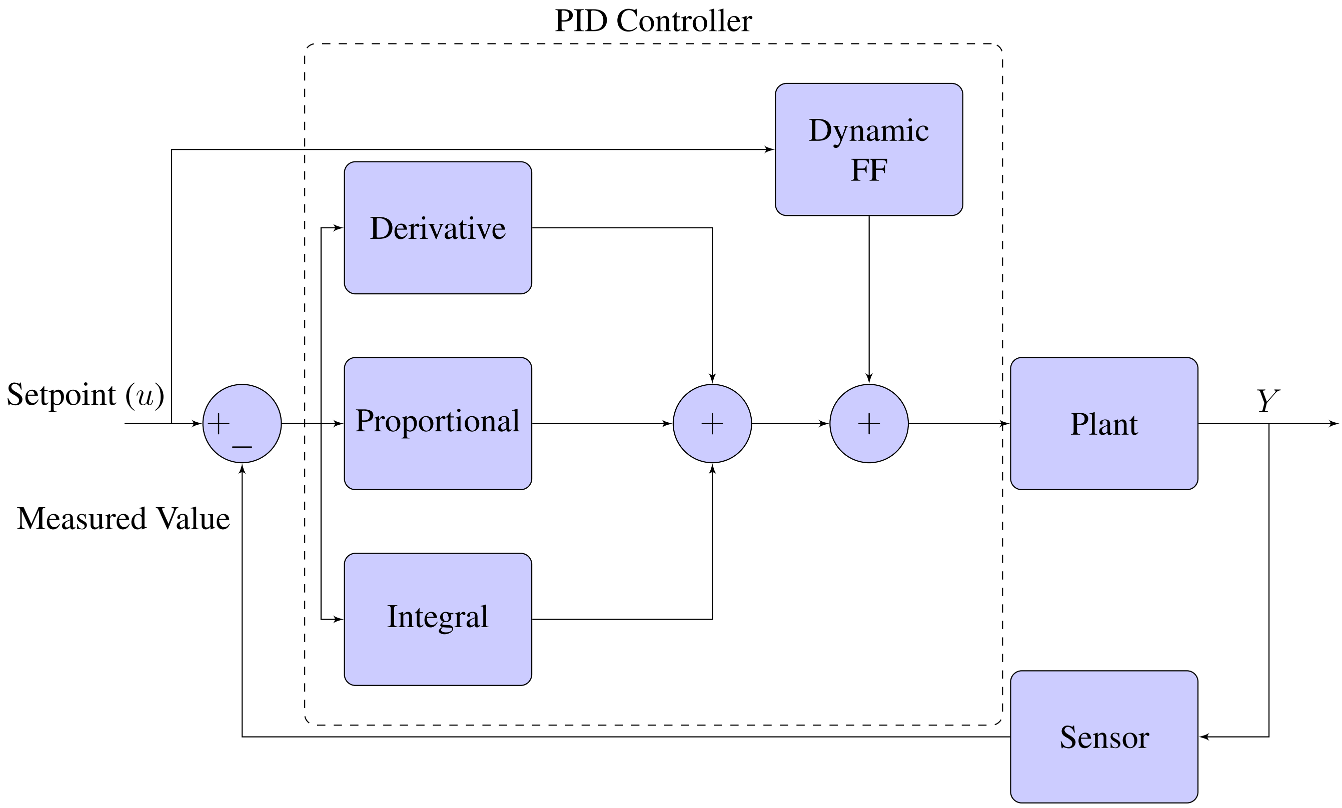


Figure 5.8: PID Controller and Dynamic Feedforward Control.

5.4.3 Zeigler-Nichols method

The Ziegler–Nichols tuning method is a heuristic method for tuning a PID

Table 5.1: Ziegler–Nichols Method Parameters for PID Controllers

Control Type	K_p	T_i	T_d	K_i	K_d
P	$0.5K_u$	-	-	-	-
PI	$0.45K_u$	$0.8\bar{3}T_u$	-	$0.54\frac{K_u}{T_u}$	-
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	$0.3\bar{3}K_u$	$0.5T_u$	$0.3\bar{3}T_u$	$0.6\bar{6}\frac{K_u}{T_u}$	$0.1\bar{1}K_uT_u$
No Overshoot	$0.2K_u$	$0.5T_u$	$0.3\bar{3}T_u$	$0.4\frac{K_u}{T_u}$	$0.6\bar{6}K_uT_u$

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.

5.5 Phase Lock Loop (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.

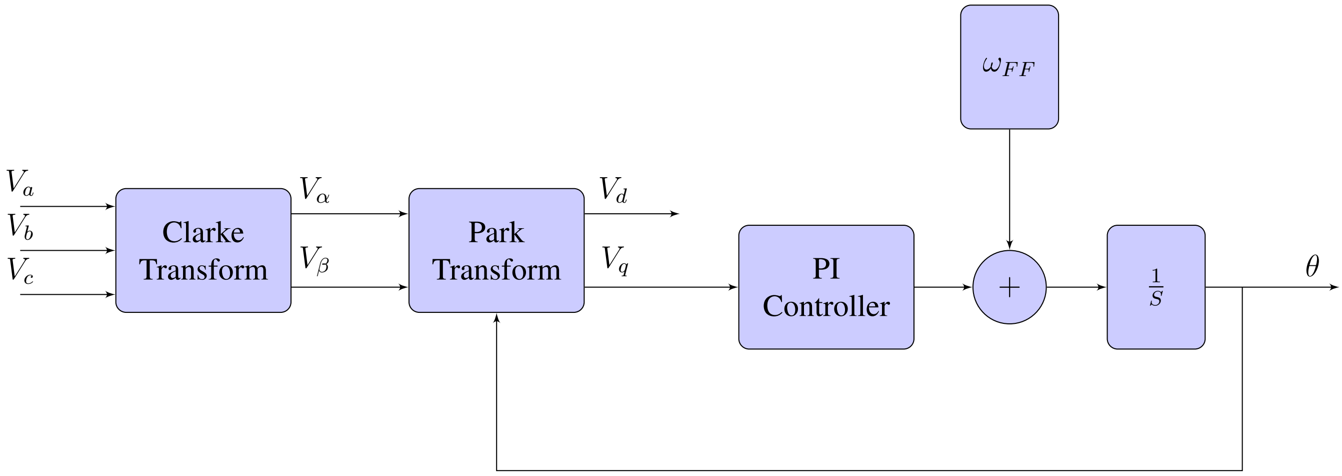


Figure 5.9: Three Phase PLL.

5.5.1 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. The transformation equations are given by:

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. The Park Transform equations are:

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.

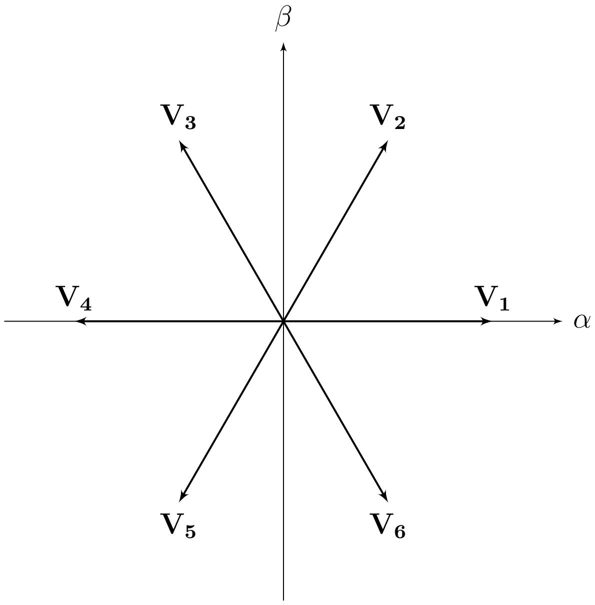
In summary, a three-phase PLL is an essential component in modern electrical and electronic systems, providing reliable synchronization and phase tracking capabilities for a wide range of applications.

5.6 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.

5.6.1 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). Below is a table outlining these basic voltage vectors:



(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 5.10: Space Vector and Switching States

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 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.

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

5.6.3 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

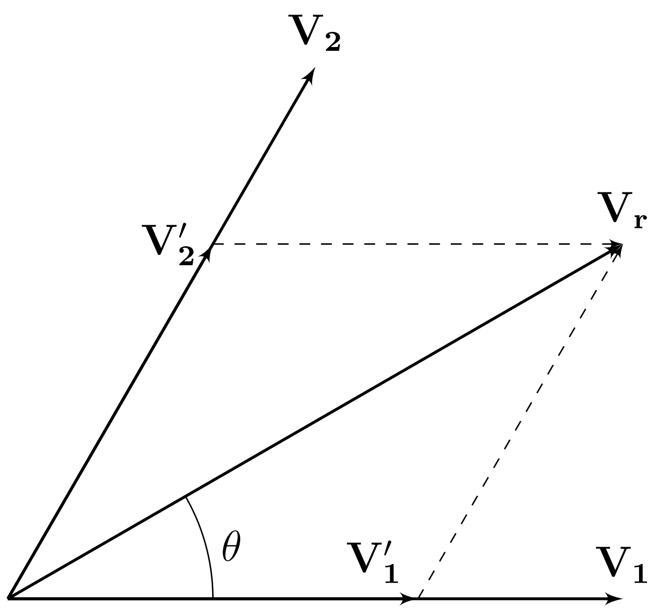


Figure 5.11: Time Interval Calculation

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, $\theta \to \theta - (N-1)\frac{\pi}{3}$:

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

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

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.

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	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 5.2: Switching Sequence for Each Sector

- **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.

5.7 Matlab/SIMULINK function blocks

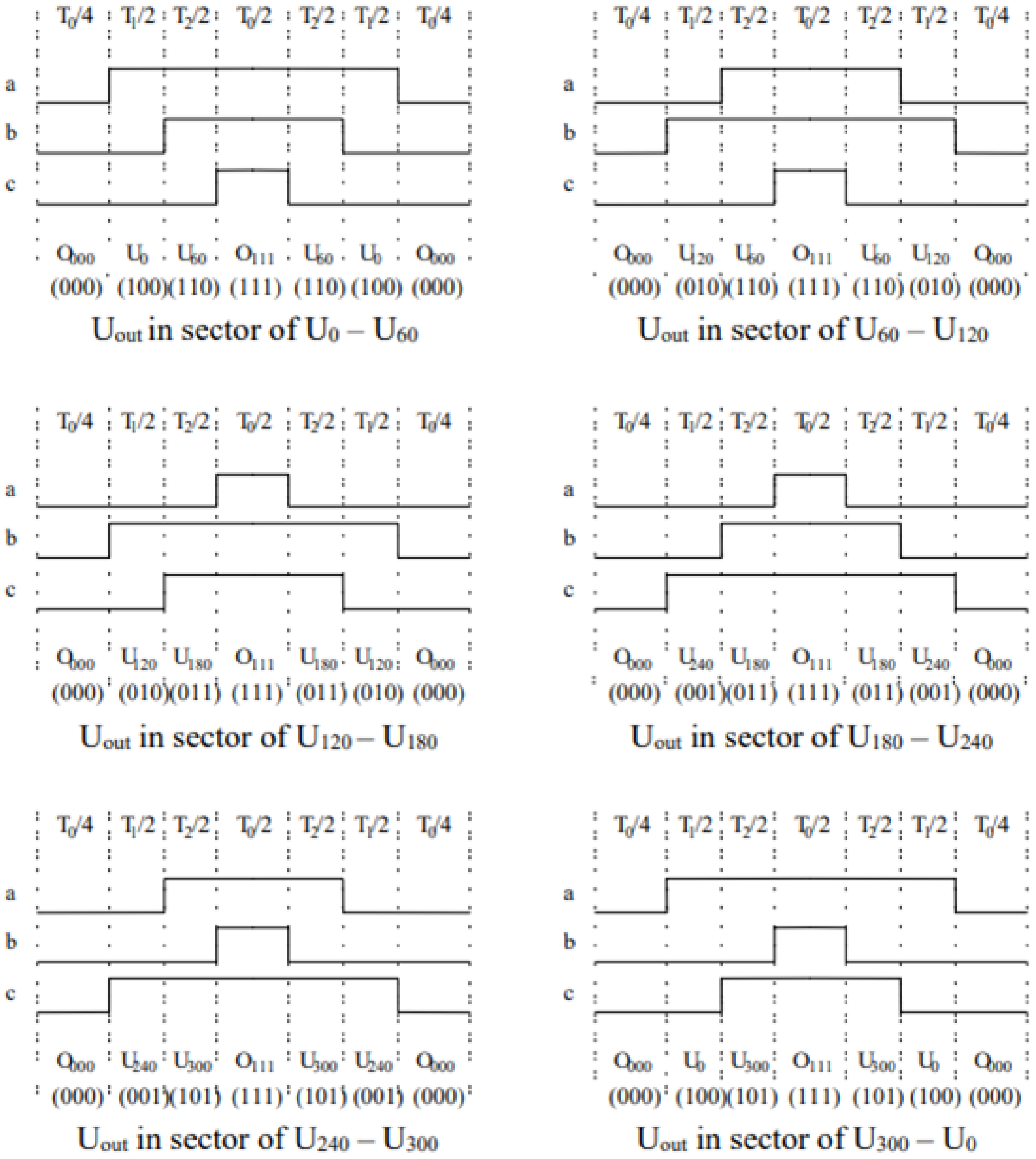


Figure 5.12: Gate Pulse Sequence

6. Conclusion and Future scope

6.1 Conclusion

Throughout my internship at Statcon Electronics India Ltd., I gained extensive knowledge and practical experience in understanding, testing, and designing LLC based resonant converters. This journey involved understanding and applying the transition from simulation to real hardware implementation.
LLC Resonant converters offers several advantages over conventional SMPS based converters, such as:

- **Higher Efficiency**: Resonant converters are more efficient than non-resonant converters because they can operate at a higher switching frequency. This reduces the amount of energy lost in the switching process.
- **Low Ripple**: Resonant converters can produce a lower ripple output voltage than non-resonant converters. This is because the resonant circuit acts as a filter, removing high-frequency components from the output voltage.
- **Wide Bandwidth**: Resonant converters can operate over a wide bandwidth. This means that they can be used with a variety of input and output voltages.

Moreover, the hands-on experience with simulation tools like LtSpice and practical circuits involving high DC voltage (upto 400V) and the complete motherboard circuit has enriched my understanding of both simulation and hardware aspects of power electronics. This dual exposure has equipped me with a holistic view of the challenges and solutions in modern power converters technology.

6.2 Future Scope

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

- **Integrated Power Supplies**: The primary use case of this LLC based resonant converter is the Integrated Power Supplies (IPS) for the railways for our company in which 4 (or more) of such converters are wired up in parallel and then used to power the load.
- **Telecom Power Supplies**: These converters can be used in telecom power supplies where the load is highly dynamic and the power supply needs to be efficient and reliable.
- **Battery Charging**: Since our design has variable output voltage with active voltage and current control, we can use it for battery charging applications in electric 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. 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.

Bibliography

[1]