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.

Mr. Sarv Parteek Singh
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Acknowledgement

I am immensely thankful for the unwavering support and guidance provided by Mr. Sarv Parteek Singh, our esteemed Technical Advisor, throughout the duration of this project.His expertise in control systems and control algorithms were invaluable in overcoming technical challenges and achieving project objectives.

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.

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:

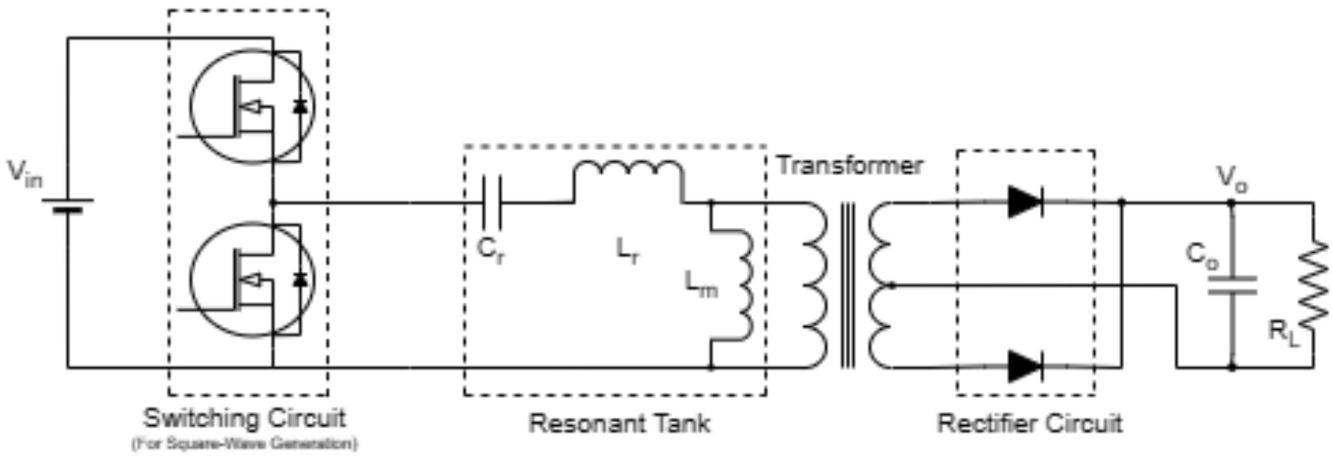

Figure 2.1: Diagram of an LLC based resonant converter

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

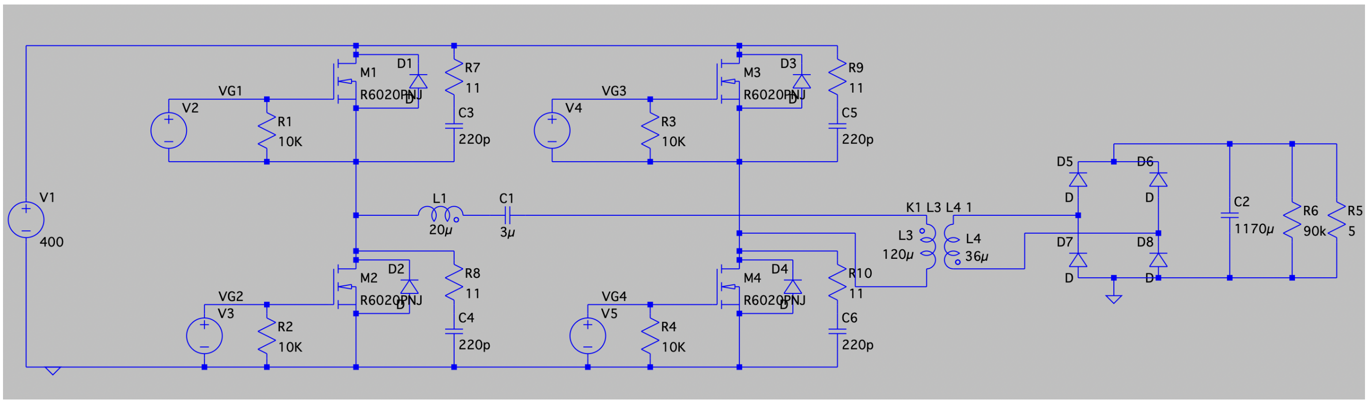

Figure 3.1: Simulation

Before initiating the design phase, it was imperative to conduct a comprehensive simulation of the existing design using LtSpice. The simulation setup (Figure 3.1) involved creating the overall circuit as well as the circuits for each individual sub-sections of the circuit and understanding as well as analyzing the behavior of each and every sub-circuit.
The output of the simulation compared with the actual output of each sub-circuit was used to analyze the behavior of the circuit and identify any potential issues that needed to be addressed before proceeding to the design phase.

3.1.1 Individual Sectional Simulation

The complete circuit was divided into multiple sub-sections and each sub-section was simulated individually to understand the behavior of the circuit.

3.1.2 Probing Data for Analysis

The data of each sub-circuit was probed with an oscilloscope and exported as a .csv file to the laptop for analysis.

3.1.3 Comparing Oscilloscope Data with Simulation Data

The simulation data and the probed data were compared against each other to understand the behavior of the circuit and identify any discrepancies.
This particular graph (Figure 3.2) is of the input and output of the gate driver circuit which is used to pull the gate of the n-channel MOSFEST.

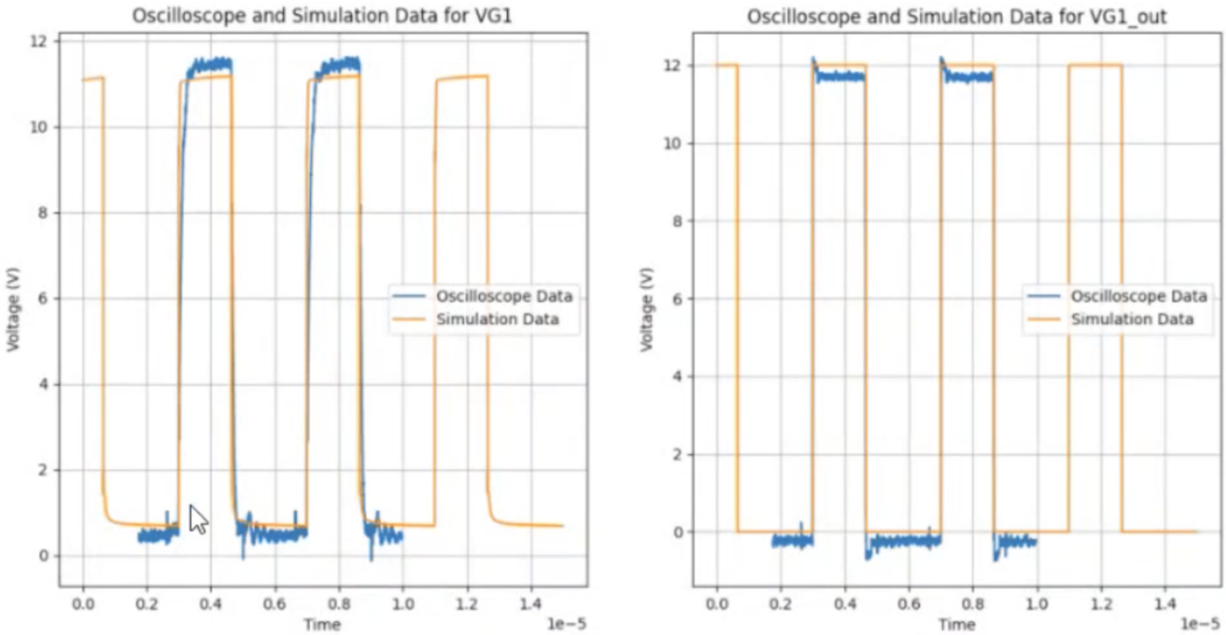

Figure 3.2: Sectional Output

3.2 Hardware Testing

The next step was to get myself involved in the hardware testing of the LLC Converter to know what all possible issues can arise in the design of such a converter or any potential things that can be improved from the current design.
This helped me learn more about the practical aspects of the design and deepened my understanding of the theoretical concepts.

3.2.1 Soldering of the Components

This involved soldering the components on the PCB and ensuring that the soldering was done properly to avoid any issues during testing. The soldering was done with lead-free solder to ensure better conductivity and reliable connections.

3.2.2 Preparing the Testing Jig of the LLC Converter

Complete testing procedure was developed which would be used to test the LLC Converter. This involved preparing the testing jig which would be used to test the converter. This needed to be done carefully to ensure that the testing was done properly and the results were accurate, and the testing jig was efficient in terms for working to ensure high productivity.

3.2.3 Debugging Hardware Issues in the Circuit

Throughout the rest of the internship, I was involved in debugging the hardware issues in the circuit and ensuring that the circuit was working properly. Multiple issues arised during the testing phase which needed to be addressed and resolved to ensure that the circuit was working properly.

3.3 Design - Calculation of LLC values

The next step was to design the LLC Converter and calculate the values of the components that would be used in the design. This involved the following steps:

- **Understanding the requirements**: Understanding the requirements of the converter in terms of input and output voltage, current, and power ratings.
- **Selecting the resonant tank components**: Choosing the appropriate resonant tank components to ensure optimal performance and efficiency.
- **Calculating the values of the components**: Calculating the values of the resonant tank components based on the requirements of the converter.
- **Designing the converter**: Designing the converter circuit based on the calculated values of the components.
- **Simulating the converter**: Simulating the converter circuit to verify its performance and efficiency.
- **Optimizing the design**: Optimizing the converter design to maximize efficiency and minimize power losses.
- **Documenting the design**: Documenting the design of the converter to ensure that it can be replicated in the future.

3.4 Suggestions in current design

Based on the simulation and analysis of the existing circuit, some changes such as change in the transformer core etc. were suggested in the design to improve the performance and efficiency of the converter.

3.5 PCB Design

The last part of my internship included designing the PCB (Figure 3.3) of some other project (RMS - Remote Monitoring System). I used Altium Designer for the same.

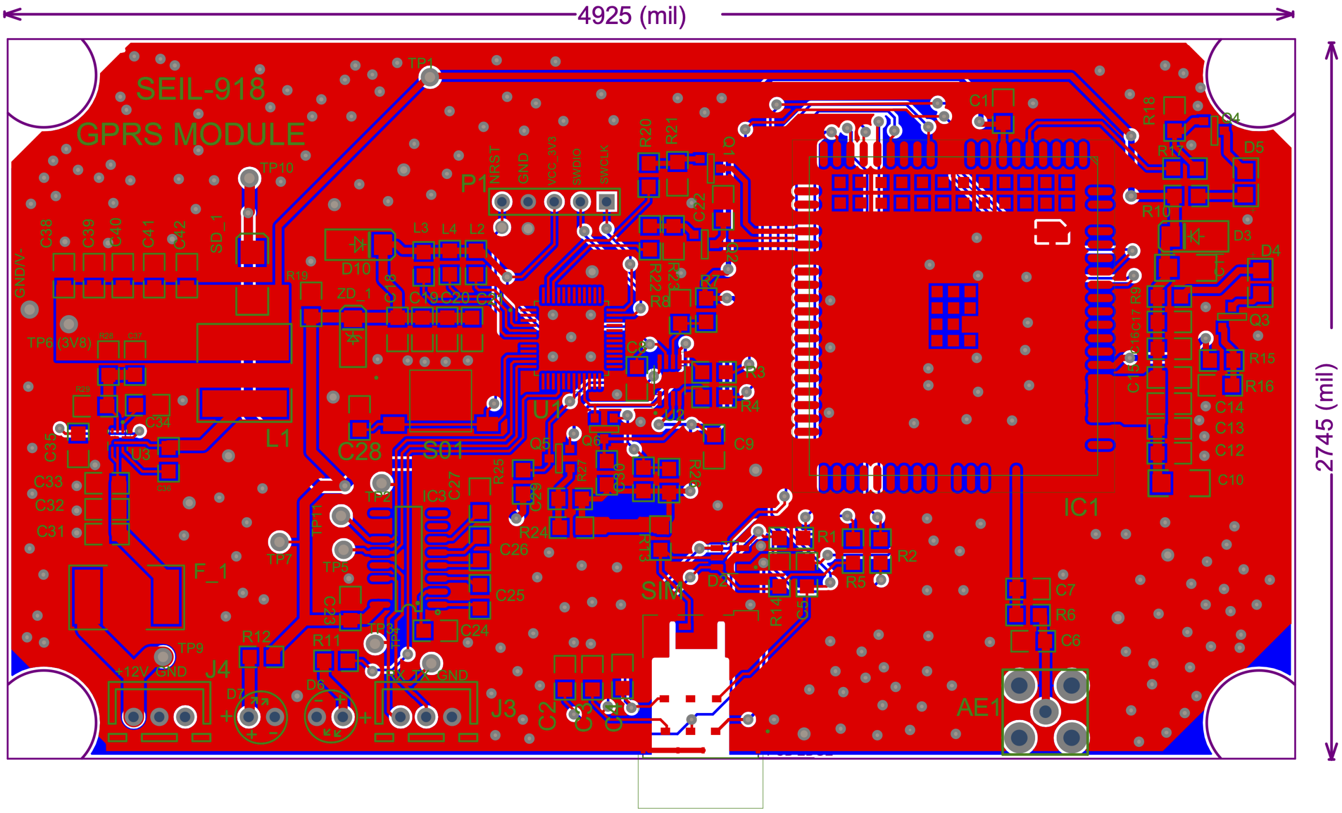

Figure 3.3: PCB

4. Review

4.1 Company Review

I had the opportunity to work with Statcon Electronics India Ltd. (SEIL) during my internship, and I am extremely pleased with my experience. One of the key strengths of SEIL is their strong technical capabilities. The team consistently delivered high-quality solutions and demonstrated a deep understanding of the project requirements. Their attention to detail and ability to solve complex problems were truly impressive. Moreover, the company's collaborative work environment fostered effective communication and teamwork. I had the chance to work closely with talented individuals who were always willing to share their knowledge and support me whenever needed. This collaborative culture greatly contributed to the success of the project. In addition, Mr. Sarv Parteek Singh provided excellent mentorship and guidance throughout my internship. The senior members of the team were always available to provide feedback, answer questions, and offer valuable insights. Their guidance not only helped me grow professionally but also enhanced my overall learning experience. This forward-thinking approach created an environment that fostered creativity and allowed me to expand my skill set. Overall, my experience with SEIL has been exceptional. Their technical expertise, collaborative work environment, and commitment to innovation make them a standout company in the industry. I am grateful for the opportunity to have worked with such a remarkable team, and I look forward to future collaborations.

4.2 Project Review

The project titled ”Design of LLC Converter” aimed to design and implement an LLC (Inductor-Inductor-Capacitor) converter for efficient power conversion. The LLC converter is widely used in various applications such as power supplies, renewable energy systems, and electric vehicles. The project started with a comprehensive literature review to understand the theoretical concepts and design considerations of LLC converters. This involved studying the operation principles, control strategies, and key components of the converter. The literature review also covered the advantages and challenges associated with LLC converters, as well as recent advancements in the field. Based on the literature review, the project proceeded with the design phase. The design involved selecting suitable components such as inductors, capacitors, and switches, and determining their values based on the desired specifications of the converter. The design also included the selection of a suitable control strategy to regulate the output voltage and ensure efficient power conversion. The existing prototype was tested under various operating conditions to evaluate its efficiency, stability, and reliability. Throughout the project, simulation tools such as LTspice were used to validate the design and analyze the converter's performance. These tools allowed for quick iteration and optimization of the design parameters. The project also included a thorough analysis of the converter's efficiency, power losses, and harmonic content. This analysis helped in identifying areas for improvement and optimizing the converter's performance. In conclusion, the project ”Design of LLC Converter” successfully achieved its objectives of designing an efficient LLC converter. The project not only provided a deep understanding of LLC converter design principles but also enhanced my practical skills in power electronics and circuit design. The knowledge gained from this project can be applied to various real-world applications requiring efficient power conversion. Future work in this area could involve further optimization of the converter design, and investigating the converter's performance under different load conditions.

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 designing of a LLC Resonant Converter.

5.1 Basics of LLC

5.1.1 Resonant Converters

Resonant converters are a type of power converter that uses a resonant circuit to store energy and provide a smooth output voltage. These converters utilize resonant circuits, consisting of inductors, capacitors, and switches, to regulate the flow of energy. They are often used in applications where a high-quality, ripple-free output voltage is required.
The resonant frequency of the converter is determined by the values of the inductor and capacitor in the resonant circuit. The output voltage of the converter is also determined by the resonant frequency.
Resonant converters are more efficient than non-resonant converters, and they can produce a higher-quality output voltage. However, they are also more complex to design and build.

5.1.2 Types of Converters and Why LLC

Now there are various types of configurations of resonant converters possible.
An ideal transformer has its magnetizing inductor in parallel with its input winding. This parallel magnetizing inductor can be used as part of the resonant circuit.

In the real world, a transformer always comes with a leakage inductor in series with the transformer windings. This series leakage inductor can also be used as a part of the resonant circuit that we intend to design.

So essentially, we require at least one inductor in series and one in parallel with the transformer for the resonant circuit that we will be designing. (We are using these inductors as part of the resonant circuit to reduce the overall cost of the circuit by minimizing the components used)

Hence, only one configuration of a resonant circuit is possible with two inductors, i.e. an LLC configuration (2 inductors + 1 capacitor)

Using an LLC Resonant circuit gives us another advantage as well, i.e. the resonant tank circuit (circuit made by the capacitor and the 2 inductors) allows for filtering of the square wave harmonics generated by the switching circuit into a sinewave of fundamental frequency for the transformer. However, the gain of an LLC Resonant Circuit is dependent on the switching frequency and the load applied across the circuit, hence it needs to be tuned considering the switching frequency and the output load to ensure that the converter efficiently operates across a wide range of loads by designing it such that the tank's gain is greater than 1 for all load values.

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

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

5.2 Simulation

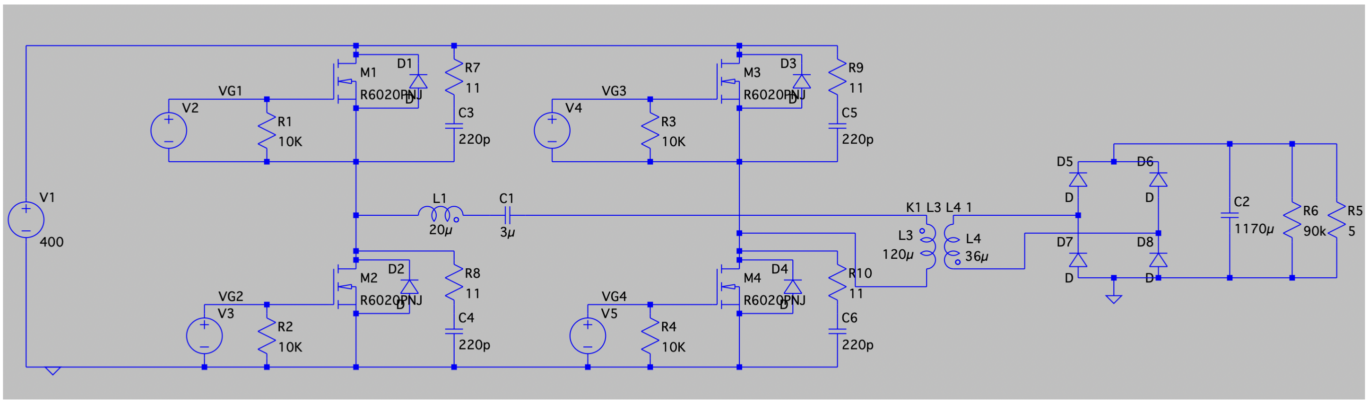

Figure 5.1: Simulation

5.2.1 Why Measure Phase Voltage?

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

5.2.2 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:

$$V_a = \frac{2}{3}V_{ab} + \frac{1}{3}V_{bc}$$
$$V_b = -\frac{1}{3}V_{ab} + \frac{1}{3}V_{bc}$$
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So, we can define the transformation matrix as:

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

5.3 Preparation of Testing Jig and Testing Procedure

5.3.1 Why Measure Phase Voltage?

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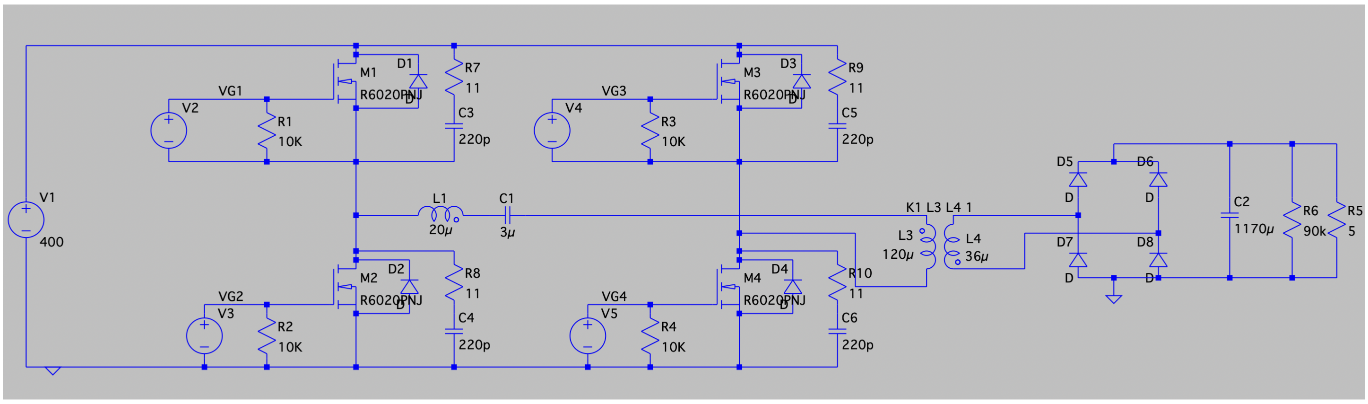

Figure 5.2: Simulation

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Solving the matrix:

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

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Thus:

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5.4 Hardware Testing

5.4.1 What is Park Transform?

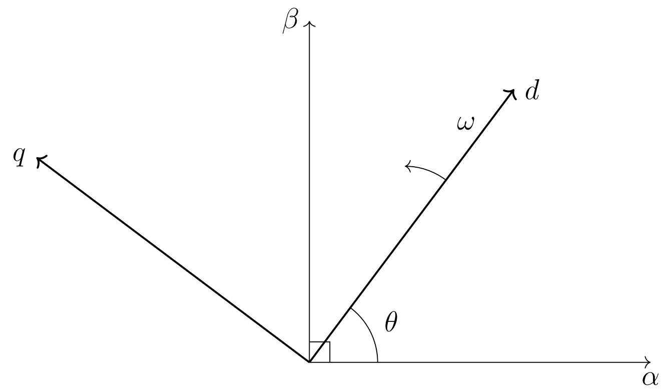

Figure 5.3: Park Frame of reference

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.

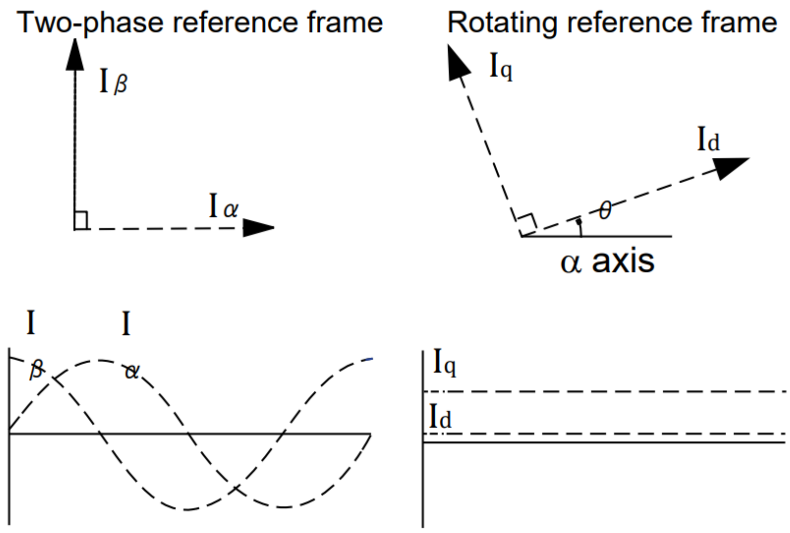

Figure 5.4: Park Transform

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}.

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

5.4.2 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:

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

Where:

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

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

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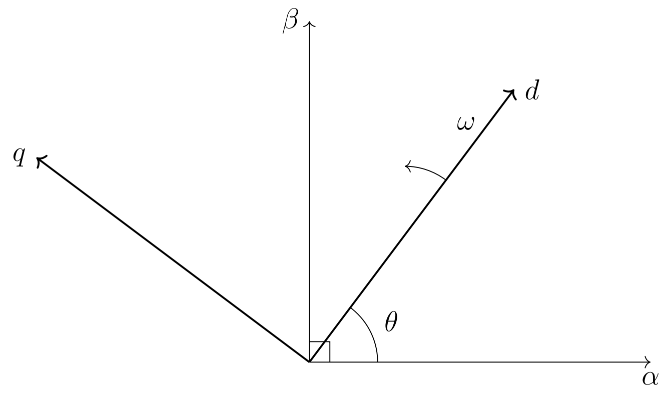
5.5 Design of LLC Converter as per 48V - 1.8kW Specification

5.5.1 What is Park Transform?



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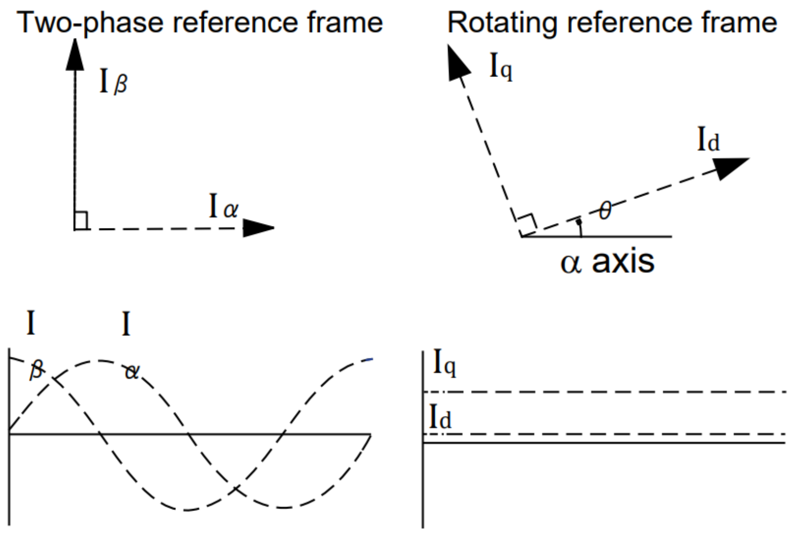

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$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix}$$

or in the shorthand notation:

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

Where:

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

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

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

5.6 Calculation of Transformer for 110V - 3kW Specification

5.6.1 What is Park Transform?

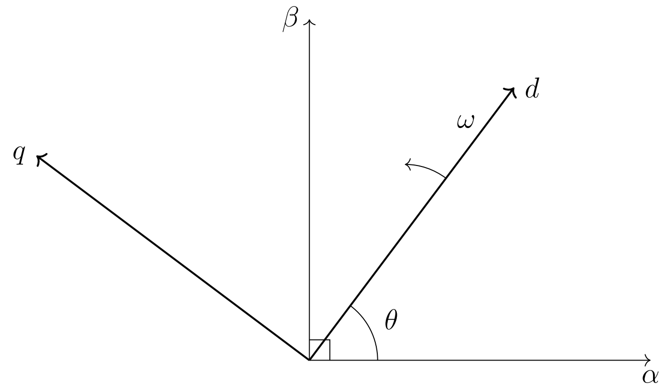

Figure 5.7: Park Frame of reference

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}.

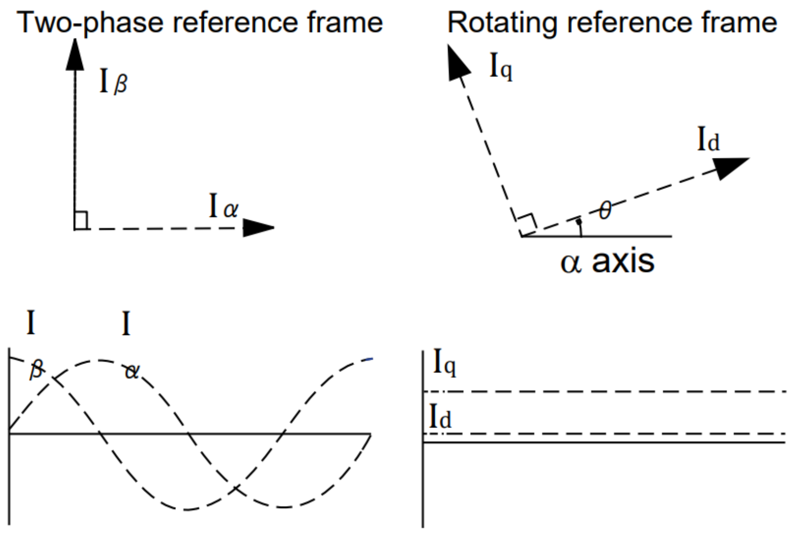

Figure 5.8: Park Transform

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

5.6.2 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:

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

Where:

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

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

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

5.7 PCB Design

5.7.1 What is Park Transform?

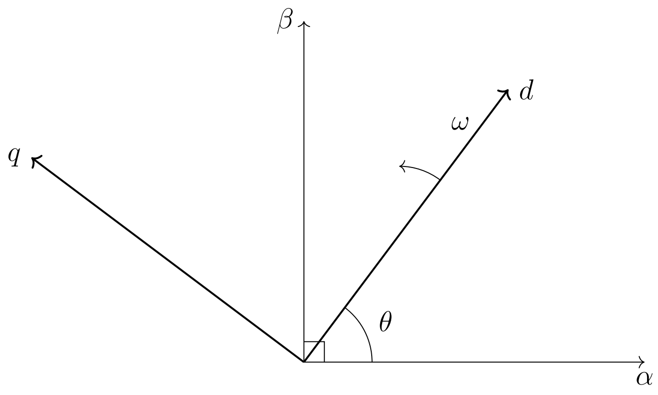

Figure 5.9: Park Frame of reference

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.

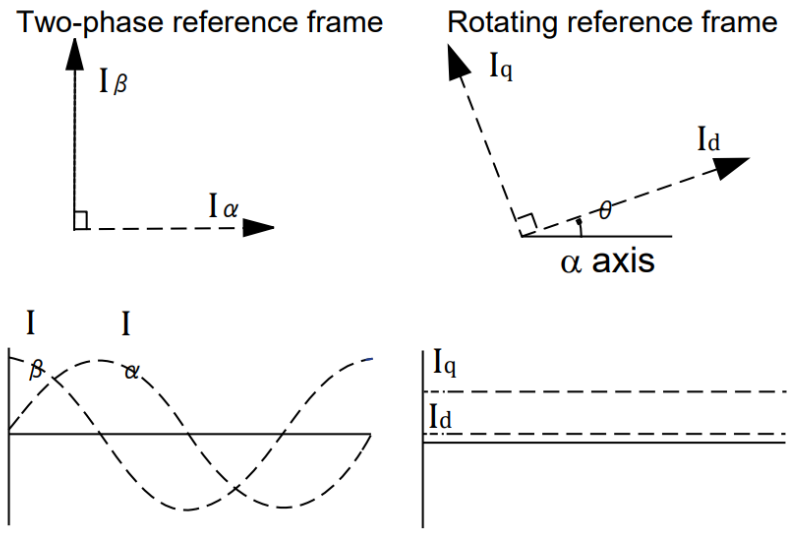

Figure 5.10: Park Transform

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}.

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

5.7.2 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:

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

Where:

$$V_{dq0} = \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$
$$V_{\alpha\beta 0} = \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix}$$
$$T_{dq0} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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.
- (Zero Voltage Switching): Resonant converters can switch at zero voltage. This reduces the stress on the switching devices and increases their lifespan.
- **Soft Switching**: Resonant converters can switch at zero current. This reduces the stress on the switching devices and increases their lifespan.
- **High Power Density**: Resonant converters have a high power density. This means that they can deliver a lot of power in a small package.
- **High Reliability**: Resonant converters are more reliable than non-resonant converters. This is because they have fewer components and operate at a lower temperature.
- **Low Electromagnetic Interference (EMI)**: Resonant converters produce less electromagnetic interference than non-resonant converters. This is because they operate at a higher frequency.
- **High Power Factor**: Resonant converters have a high power factor. This means that they can deliver power more efficiently. (Our Design incorporates a PFC before the LLC, so the power factor is at the supply side is close to 1)
- **Active Voltage and Current Control**: Active voltage and current control which ensures that the output voltage and current are always in control and the converter is always in a stable state.

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.
- **Renewable Energy Systems**: These converters can be used in renewable energy systems like solar and wind power systems where the input voltage is highly variable and the power supply needs to be efficient.
- **Medical Equipment**: These converters can be used in medical equipment where the power supply needs to be reliable and efficient.
- **Industrial Automation**: These converters can be used in industrial automation where the power supply needs to be efficient and reliable.

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]