Project Report

(Internship Semester January–June)

Design of LLC Based Resonant Converter

Submitted by

Soumil Arora
21105005

Under the Guidance of

Mr. Sarv Parteek Singh
Technical Advisor
Statcon Electronics India Ltd,
Noida

Assistant Professor Muzaffar Imam
Faculty Coordinator
Electronics and Communication Engineering
Punjab Engineering College (Deemed to be University),
Chandigarh

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

Soumil Arora
21105005

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

Mr. Sarv Parteek Singh
Technical Advisor
Statcon Electronics India Ltd,
Noida

Assistant Professor Muzaffar Imam
Faculty Coordinator
Department of Electronics and Communication Engineering
Punjab Engineering College (Deemed to be University),
Chandigarh

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.

Soumil Arora
21105005

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:

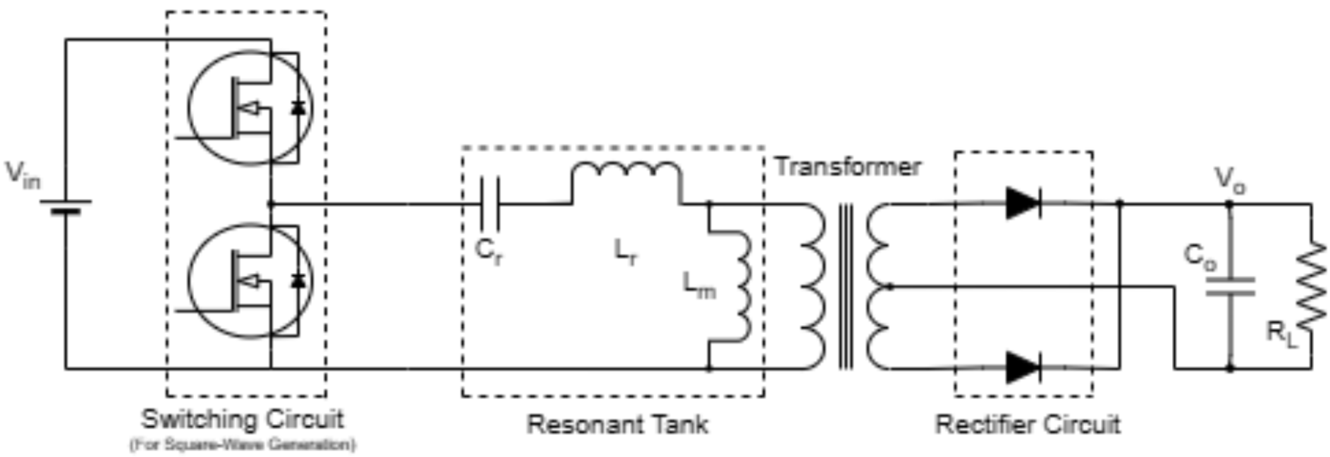

Figure 2.1: Diagram of an LLC based resonant converter

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.
- **Load Sharing**: The biggest challenge was when we hooked up multiple LLCs in parallel to perform load sharing and we observed oscillications in the load shared. This was solved later by my analysis of the circuit.

3. Summary of Work

3.1 Simulation

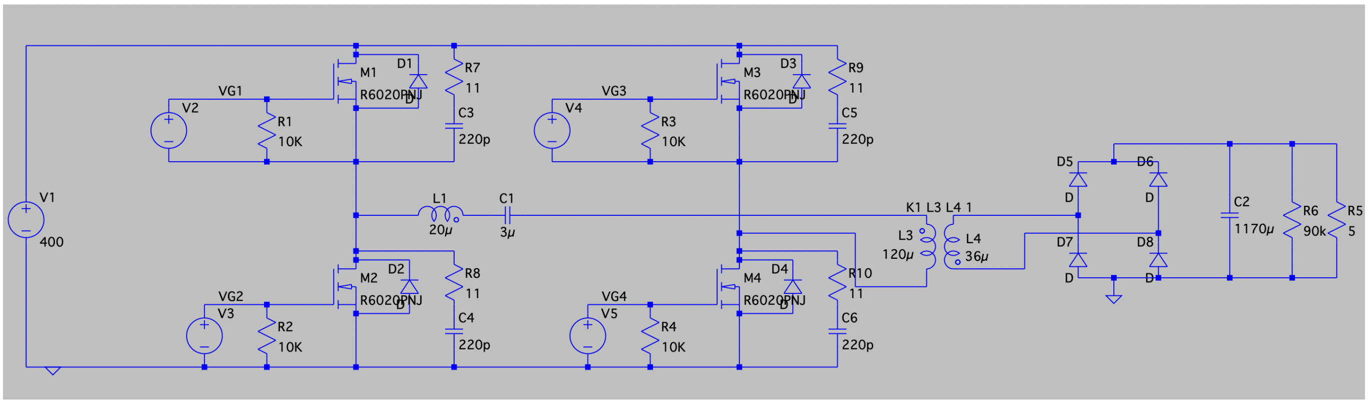

Figure 3.1: Simulation

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.

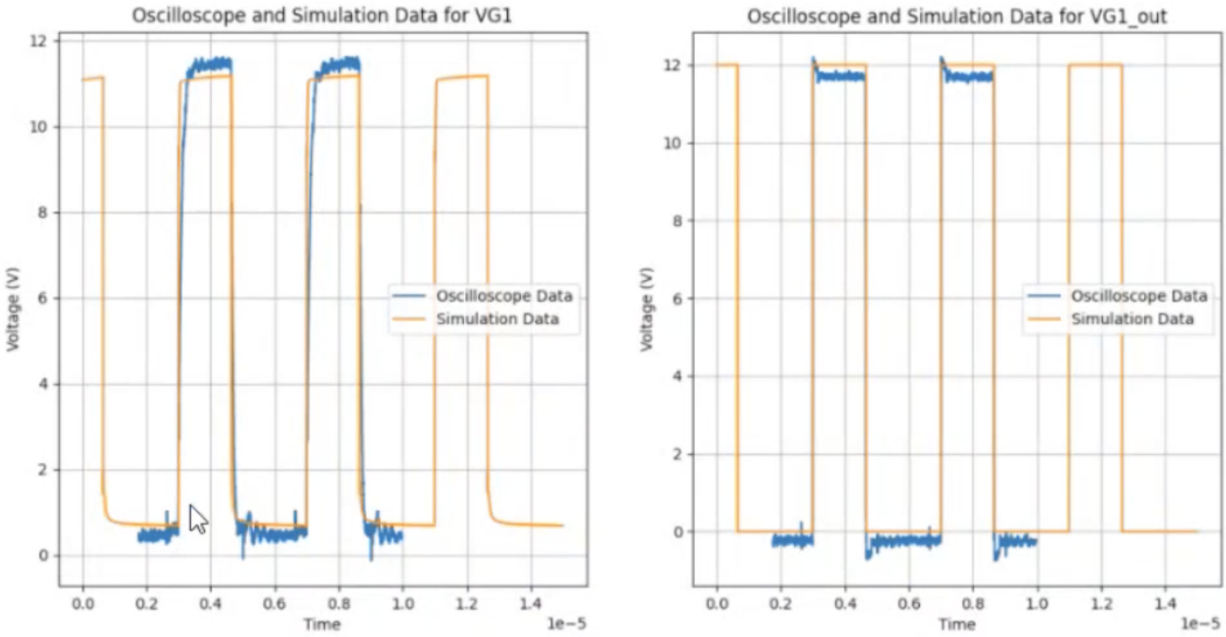

Figure 3.2: Sectional Output

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.

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 (such as issue in the feedback signal, issue with the boosting of the voltage, correct mapping of status LEDs to the corresponding pins on the microcontroller) arised during the testing phase which needed to be addressed and resolved to ensure that the circuit was working properly. The biggest challenge was when we hooked up multiple LLCs in parallel to perform load sharing and we observed oscillications in the load shared. This was solved later by my analysis of the circuit.

3.3 Frequency-Gain Curve Plotter for LLC Converters

Based on the literature that I read during the course of my internship, I made a generalised Frequency-Gain Curve Plotter for the LLC Converter. This plotter would help in understanding the behavior of the converter and would be useful in designing a converter. All we need to do is input our requirements (such as minimum and maximum output voltage, desired resonant frequency, output power) and one or two variables that we choose according to our design and we would get the Frequency-Gain curve for the converter, basically the response of the LLC tank (Gain) for various switching frequencies and then we can tune out the values by optimising the graph as per our requirements.

3.4 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.

3.5 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. These changes arised by noting that the maximum heat is generated in the transformer only in the current design, so we can improve the efficiency of the current converter as well by changing the transformer core. The suggested core was PQ40/40 core with PC47 material which has the required power handling capacity, is smaller in terms of footprint, lower EMI noise, and has better efficiency for our operating frequencies. Morever, it is Rs. 70 cheaper than the current core (so if we sell 20,000 units of this power supply, we can save Rs. 14,00,000).

3.6 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.

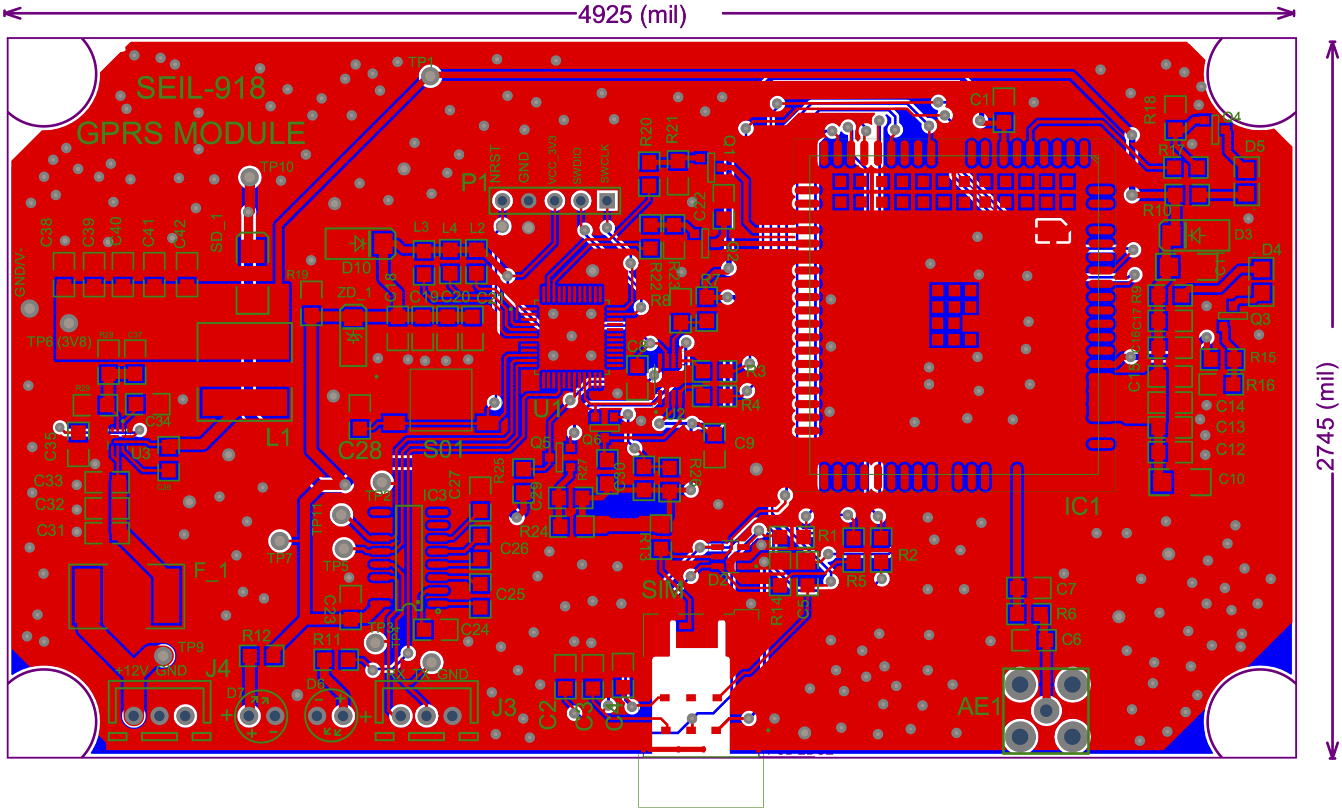

Figure 3.3: PCB

4. My 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.

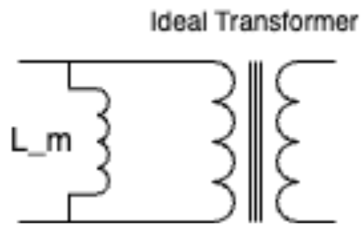

Figure 5.1

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.

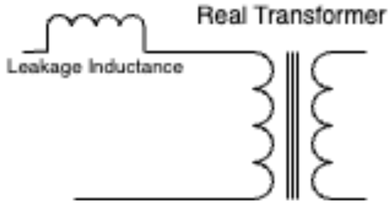

Figure 5.2

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)

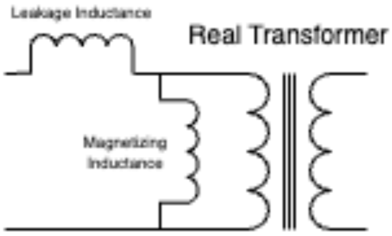

Figure 5.3

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

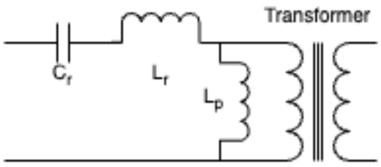

Figure 5.4

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 as per our requirements.

5.2 Simulation

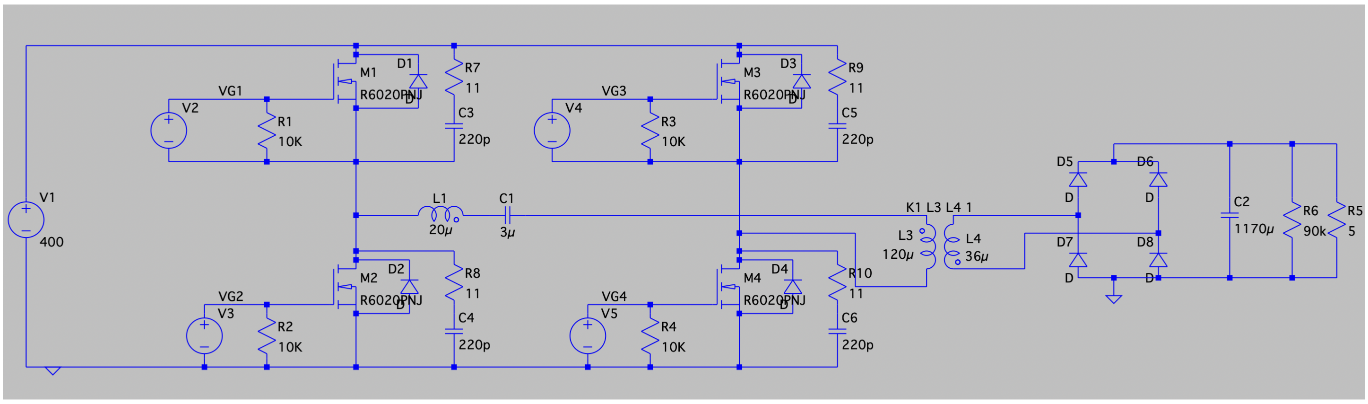

Figure 5.5: Overall Circuit of the LLC Converter

5.2.1 Sectional Analysis

One of my first tasks was to perform a sectional analysis of the complete motherboard and control board circuit. Since active feedback is not possible in LtSpice, I decided to split the complete circuit into multiple sections, such as gate driver circuit, switching circuit, voltage feedback op-amps and circuit, etc. and then simulate them individually.

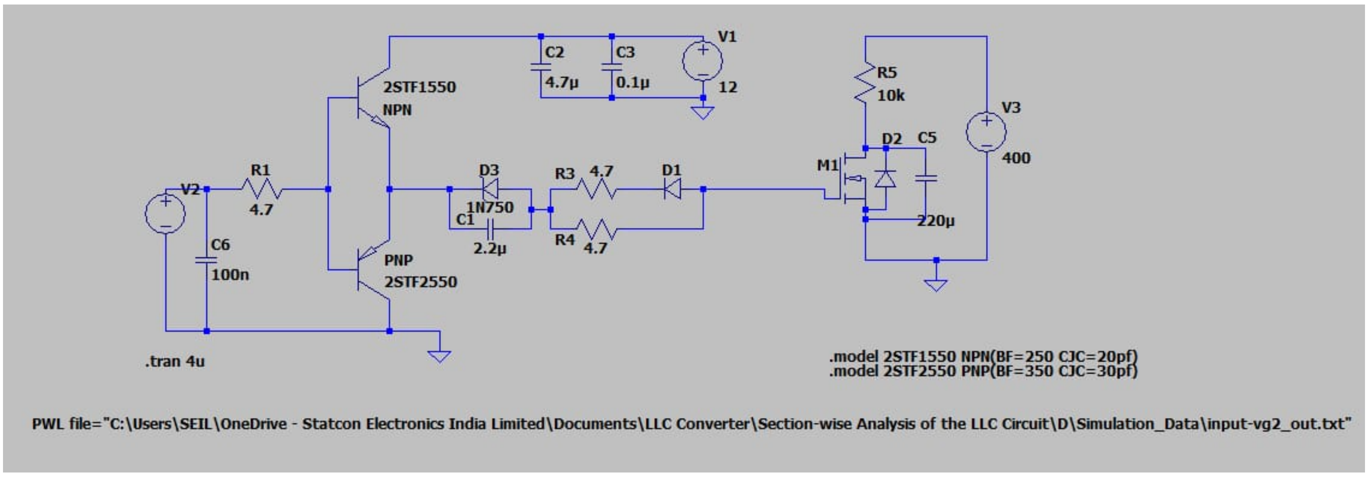

Figure 5.6: LtSpice circuit of the gate driver circuit

One such circuit is shown in figure 5.6 The circuit shown above is of a gate driver circuit. This circuit is responsible for driving the MOSFETs in the switching circuit. The input to this circuit is a signal coming from the gate driver IC which in turn receives the signal generated by the microcontroller. The output of this circuit is the gate signal for the MOSFETs.

5.2.2 Probing Actual Data

To ensure that the hardware circuit is functioning as expected, data was probed using an oscilloscope with isolated probes (so as we do not to mess up the Gate signal of the MOSFETs while probing the data) as shown in figure 5.7

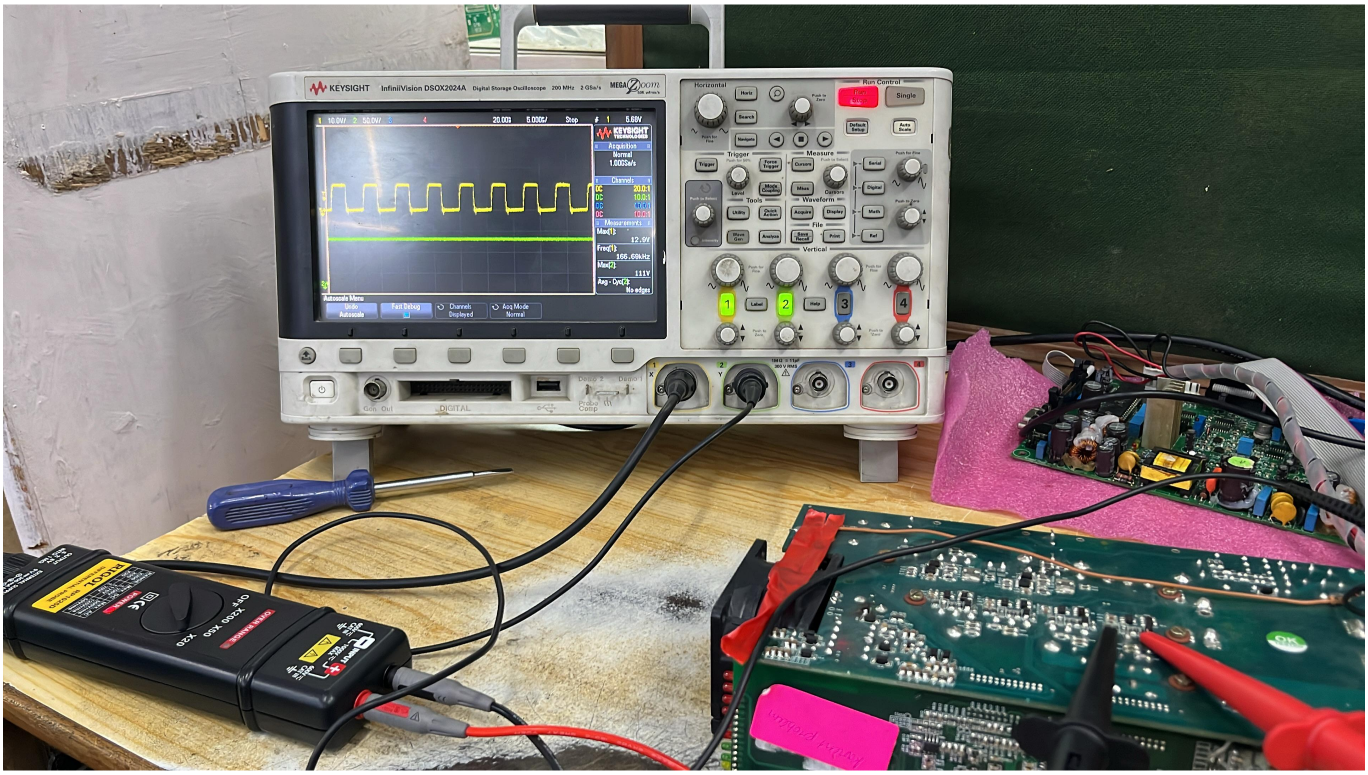

Figure 5.7: Probing Gate Signal using isolated probe

5.2.3 Comparitive Analysis of Simulated Data with Actual Data

The data obtained from the simulation was compared with the data obtained from the oscilloscope to ensure that the circuit is functioning as expected. This was done by writing a python script (.py file) which reads the data from the file generated by the oscilloscope as well as the file generated by LtSpice and then plots them on the same graph. (Figure 5.8)
To ensure that the simulation of the sub-circuit is accurate, and to minimise the effect of ideal conditions in a simulation, the input to the sub-circuit was taken from the probed data, and then the output was plotted according to the actual input to that sub-circuit.

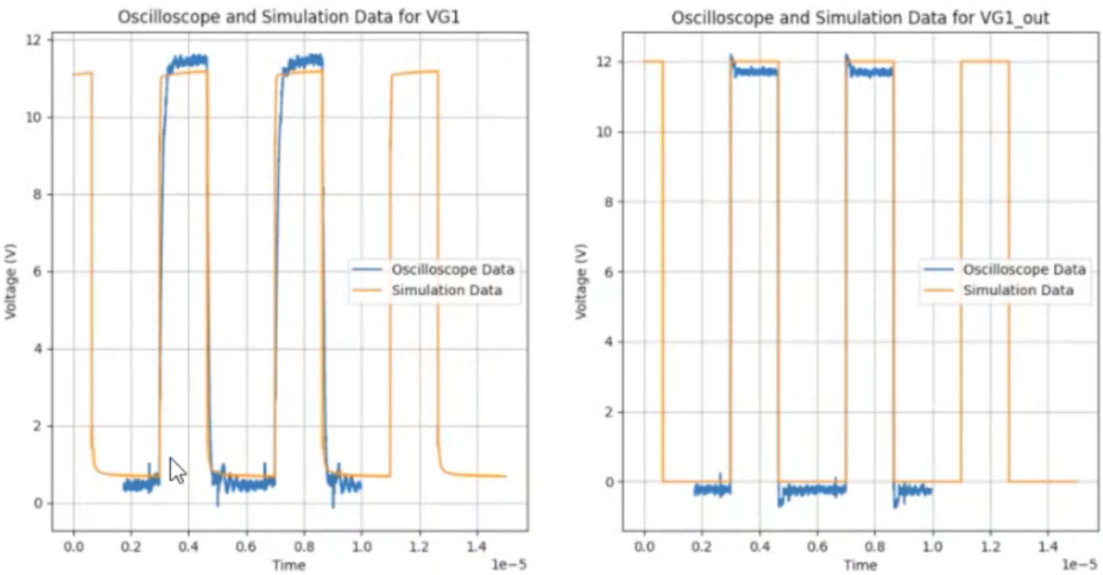

Figure 5.8: Comparision of Simulated and Probed Data for 2 signals

5.3 Preparation of Testing Jig and Testing Procedure

5.3.1 Overview

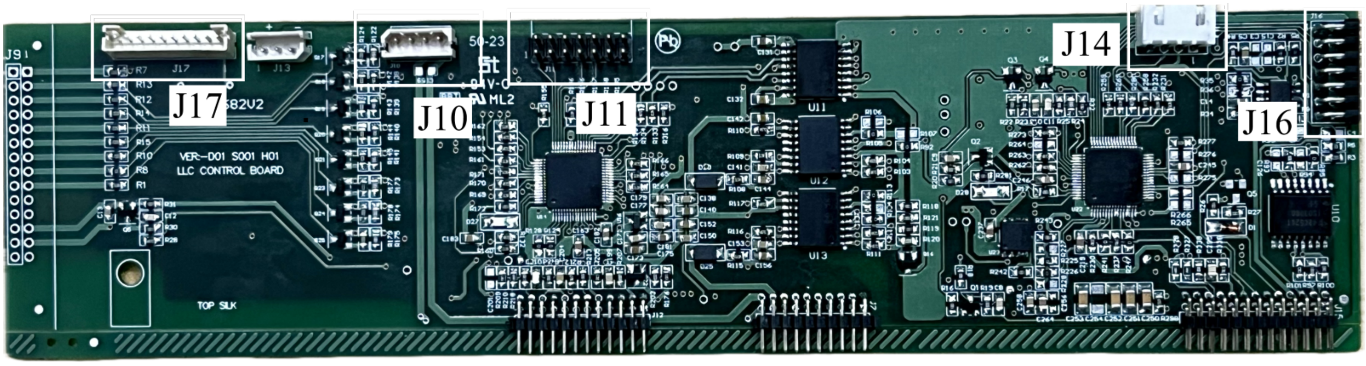

Figure 5.9: Control Board Circuit

- J10 – Connector for Fan
- J11 – Connector for programming the PF
- J16 – Connector for programming the LLC
- J14 – Connector for debugging (Optional – after complete assembly, J7, RS485 connector on motherboard will be used)
- J17 – Connector for Display

5.3.2 Pre-Testing

Safety Equipments

Wear Safety Equipments such as Insulated Rubber Gloves (Figure 5.10), and earthing band (Figure 5.11) before beginning with the testing

Figure 5.10: Insulated Rubber Gloves

Figure 5.11: Earthing Band

Visual Inspection

The first and foremost part of testing any product involves visually inspecting the PCB to ensure correct component placement as per the schematic and the BOM (Bill of Materials). This also ensures prevention of any physically damaged PCBs to go further the testing line.

5.3.3 Control Board Testing

Programming the LLC and PFC with Drive-check codes

- Connect J16 to the programmer and upload the LLC drive check code.
- Connect J11 to the programmer and upload the PFC drive check code.

(Refer to Figure 5.9 for the position of the connectors)

Circuit Connections

- Connect the control card to a tested motherboard as shown in Figure 5.12.

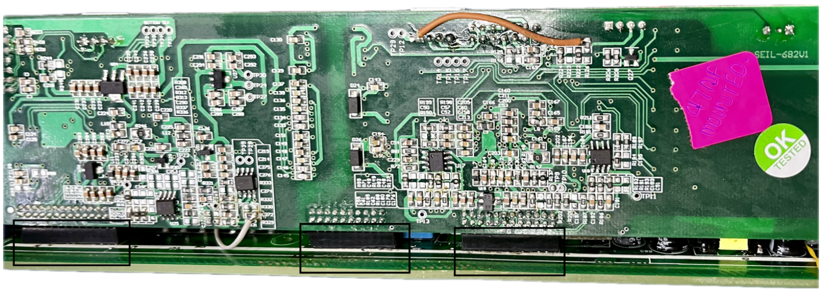

Figure 5.12: Headers of the control card to the motherboard

- Connect the cooling fan to the fan connector at J10 (Figure 5.13).

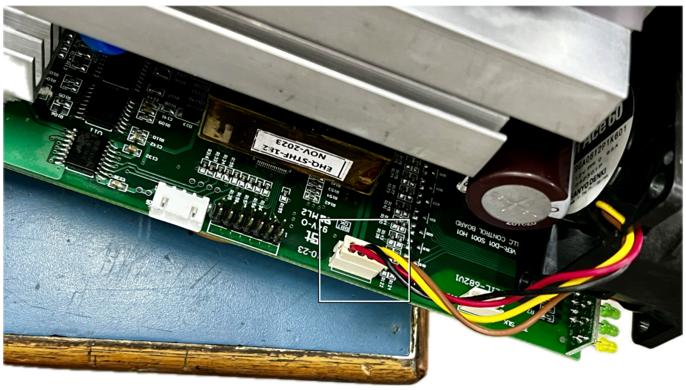

Figure 5.13: Fan Connector at J10

- Ensure no AC supply is connected, and only external DC supply (350-400V) is connected to the motherboard.
- Connect display connector (at J17), with one-to-one matching (pin 1 is connected to pin 1, pin 2 to pin 2 and so on... - Figure 5.14).

Figure 5.14: Display Connector at J17

Check the Drive (Gate signals at MOSFETs)

- Using an oscilloscope, probe the gate voltages of the MOSFETs of PFC and LLC one-by-one to ensure that all MOSFETs are receiving a PWM signal (square wave type) at their Gate. (probe between 1st and 3rd legs).

Upload Final Code

- Connect J16 to the programmer and upload the LLC final code.
- Connect J11 to the programmer and upload the PFC final code.
- Connect laptop to J14 and run mainfile.py. Check that all the measured values are correct. (Such as current – 0A, boost voltage – 0V etc.) - Figure 5.16

5.3.4 Mother Board Testing

Supply Section Check

- Connect an external DC supply (350-400V) to the circuit (At output of PFC - Figure 5.15).

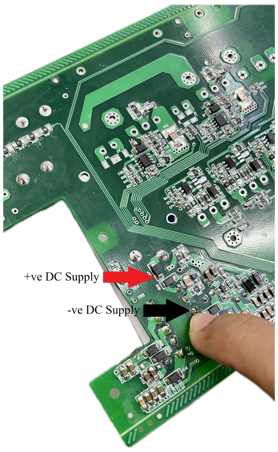

Figure 5.15: Connecting DC Supply

- Once it is switched ON, using a multimeter, check the voltages across the following capacitors for confirming the power supply section.
  - C113 – 5V (unregulated)
  - C100 – 12V
  - C94 – 3.3V
  - C106 – 12V (unregulated)

Programming the LLC and PFC with Drive-check codes

- Connect J16 to the programmer and upload the LLC drive check code.
- Connect J11 to the programmer and upload the PFC drive check code.

(Refer to Figure 5.9 for the position of the connectors)

Circuit Connections

- Connect the tested control card (with drive check code) to the motherboard as shown in Figure 5.12.
- Connect the cooling fan to the fan connector at J10 (Figure 5.13).

Check the Drive (Gate signals at MOSFETs)

- Using an oscilloscope, probe the gate voltages of the MOSFETs of PFC and LLC one-by-one to ensure that all MOSFETs are receiving a PWM signal (square wave type) at their Gate. (probe between 1st and 3rd legs).

Upload Final Code

- Connect J16 to the programmer and upload the LLC final code.
- Connect J11 to the programmer and upload the PFC final code.
- Connect laptop to J14 and run mainfile.py. Check that all the measured values are correct. (Such as current – 0A, boost voltage – 0V etc.) - Figure 5.16

5.3.5 Assembled Testing

Make Final Connections

- Remove DC supply and connect AC supply (150V - 270V RMS) to the motherboard (at J1).
- Remove laptop connector at J14.
- Connect RS485 connector to J7.
- Connect DSA Comm. connector at J3 (for communication regarding battery charging).
- Turn ON the AC Supply.

Run Debugging Tool in Laptop

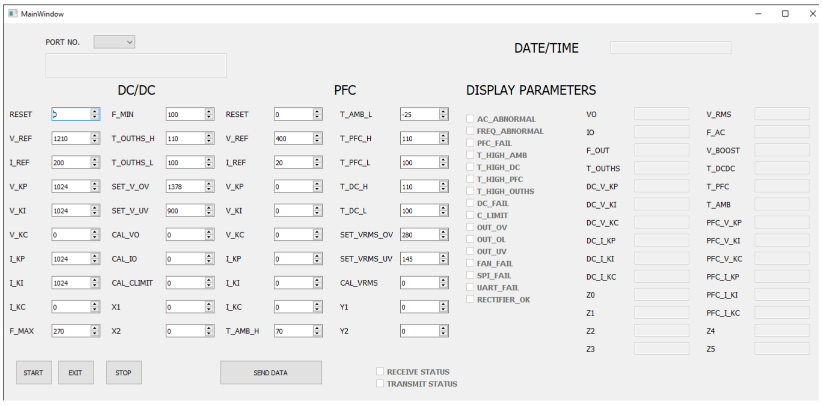

Figure 5.16: Debugging Tool

- Run mainfile.py on the laptop and then connect it to the motherboard (by pressing START).
- Click on SEND DATA.

Verify all functionality

- Verify the data displayed on the screen with the actual readings of the input voltage, output voltage, output current and temperatures to ensure that all feedback mechanisms are working correctly.
- Ensure all LEDs are working according to their functions by giving faults (such as giving over voltage at input – 280V RMS, increasing load beyond 20A, when in boost – LED2 will on, etc.)

5.4 Hardware Testing (R & D of the Product)

Figure 5.17: Hardware Testing Setup

Figure 5.18: The load that we made for testing

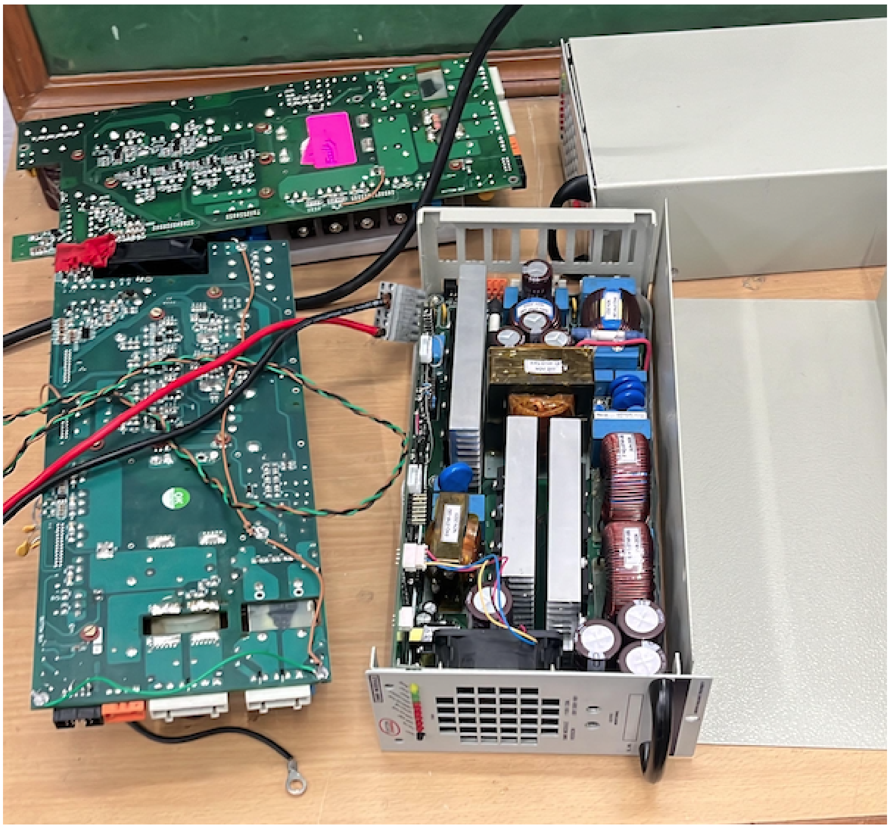

Figure 5.19: The assembled circuit

Figure 5.20: Completely assembled circuit

During the hardware testing and debugging of the circuit, I faced many issues to resolve, some of which were:

- **Issue in the voltage feedback signal**: The output voltage was having fluctuations, which we found out was because of noise in the feedback signal of the voltage produced.
  To overcome this issue, we experimented with various values of voltage divider resistors, and capacitors so as to minimise the noise in that signal and somewhat stabilize the output.

- **Issue with boost of the converter**: The converter did boot up properly (going from 90V at startup to 120V, which is the voltage at the resonant frequency as well), but if wouldn't go past that (it should go till 150V). Though this issue was observed only in some converters and rest did not have this issue, the cause of this issue needed to be found out to ensure reliablility across products when it's finally put into production.
  The issue was identified as noise in the connector which carries the "Set output DC Voltage" signal (basically the DC output voltage which it must make), which is sent with the DSA Board (another board which is connected to the motherboard which communicates with the battery etc and conveys the information as set output voltage, maximum current flow etc. to the LLC Converter control board).
  The issue was resolved by passing the connector through a ferrite bead (Figure 5.21). This acts a common-mode choke and helps filter out the common-mode noise, allowing only differential signals to pass through. It also helps in controlling the impedence ensuring signal integrity over the length of the connector.

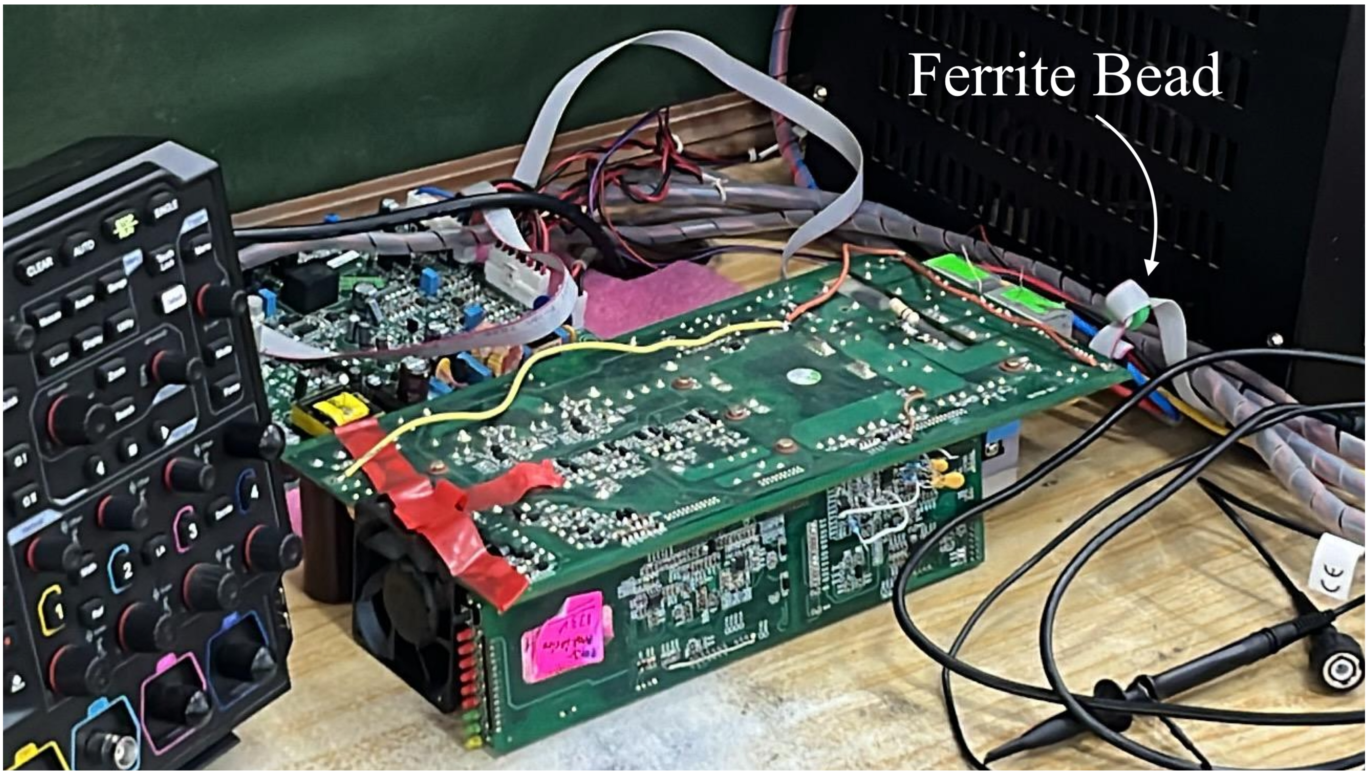

Figure 5.21: Ferrite Bead (See Arrow)

- **Load Sharing**: The ultimate aim of our converter is that multiple converters will be hooked up in parallel connected to a single DSA board (which will let know each one of them about the desired voltage etc.).
  When we did that, the issue was that, say we have a load that requires 10A and we have 2 converters connected, so ideally both should output 5A for equal load sharing but the issue was that it booted up fine (with minor oscillations, of 0.5-1A) but as soon as there was a change in load, say the load increased to 20A, now each should output 10A, but there were huge oscillations in this, as well as the output voltage each one was producing. The oscillations in current were as large as 5A (like at some moment, one is giving 5A and other is giving 15A, and after some moments, the first one is giving 15A, while the second one is giving 5A).
  By my detailed analysis of the schematic, we figured out that this issue was because of the position at which we were measuring the output voltage and current of each converter for feedback and active control (FIgure 5.22). There was a separate reference for the feedback signal and the output voltage and because of presence of a fuse, reverse current protection diode and a choke between both these points (to reduce the output voltage ripple), there was a difference in the potentials of actual voltage at output, and the voltage measured for feedback (although the difference was in mV, $20mV$ is just because of the shunt resistor of $1m\Omega$ through which current is flowing (current flow at full load = 20A), but enough to cause oscillations in the output voltage, and hence output current).
  We resolved this issue for now by adding a current dependent offset for the voltage drop (by multiplying the measured current flowing by the resistance, this is a generalised value for each converter), but in the next version of the PCB, we will add a summing op-amp into the feedback signal to account for this difference in the potentials, which would eliminate the need for adding a offset, or change the position of voltage feedback altogether.

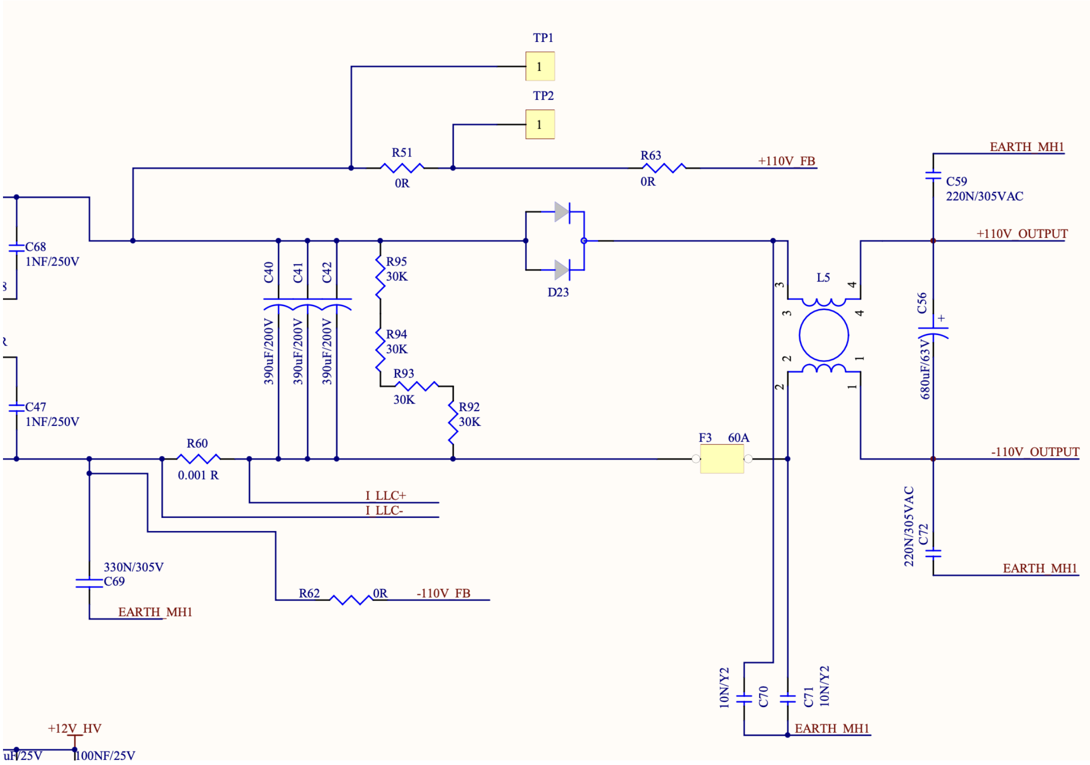

Figure 5.22: Part of schematic which shows the position at which the feedback signal was taken, which was causing the load sharing issue

5.5 Frequency-Gain Curve Plotter for LLC Converters

As per the literature I read during the initial part of my internship, I designed a generalised circuit (Figure 5.23) that takes just the basic required paramteres of any LLC Converter, and calculates the rest accordingly, and give us the theoritical plot of the frequency-gain curve of the converter, which mostly coincides with the actual plot of the gain v/s frequency as well. (Verified that experimentally by measuring the frequencies at multiple points and calculating the gain of the LLC tank at that instant and plotting it against the frequency at that instant)

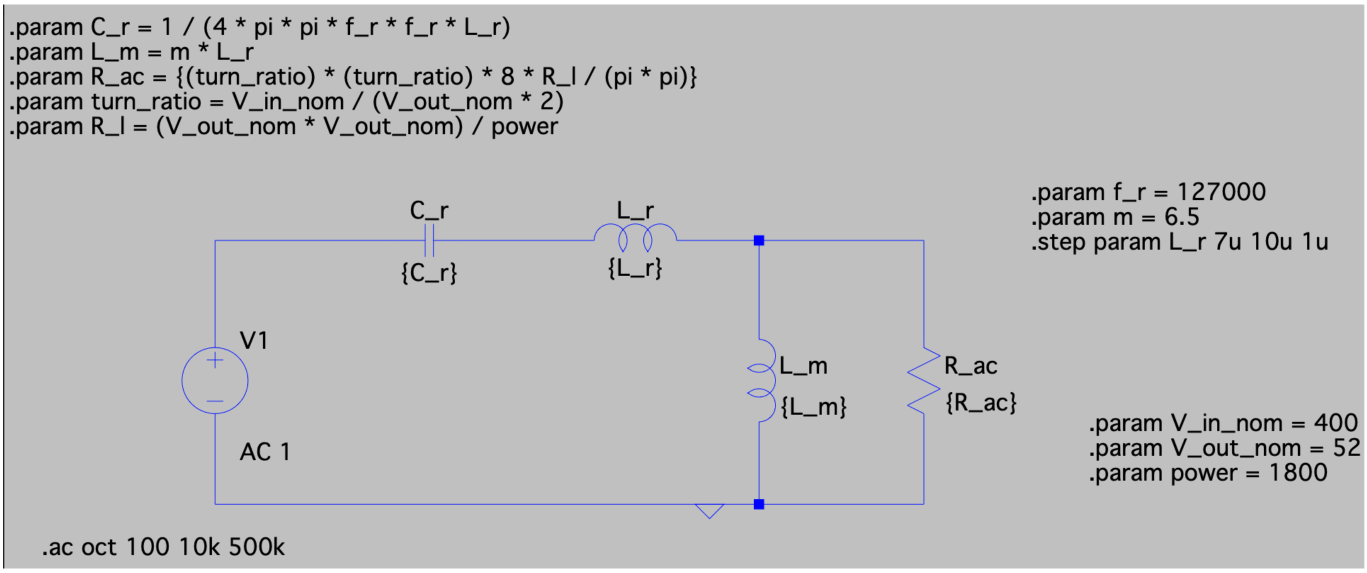

Figure 5.23: Schematic of the frequency-gain curve plotter

- The bottom-right parameters are from the required specifications, i.e., the nominal input volage, nominal output voltage, and the rated maximum power of the converter.

- The centre-right parameters are of the resonant frequency that we want for our design (usually 100-150 kHz for a SMPS), the value of m (The ratio of magnetizing inductor to the series inductor = L_m/L_r)
- The .step parameter is used to generate multiple graphs at the same time with different specs (for example, the given graph (Figure 5.24), shows multiple graphs for different combinations of LLC simultaneously). This helps in fine-tuning the values according to our gain requirements.
- The top-left parameters are equations and other variables that are dependent on the values that we give as input.
- The bottom-left parameter is the range of frequencies between which we want to plot the graph. (As per the current circuit, between 10kHz to 500kHz with step size of 100Hz)
- R_{ac} is the equivalent resistance of the transformer, rectifier, and the output filter in the circuit.
- The input to the circuit in simulation is a AC signal of 1V amplitude and 0V DC offset. (This is done in order to simplify calculations; The value of voltage in the output waveform is the value of gain of the LLC Tank only)

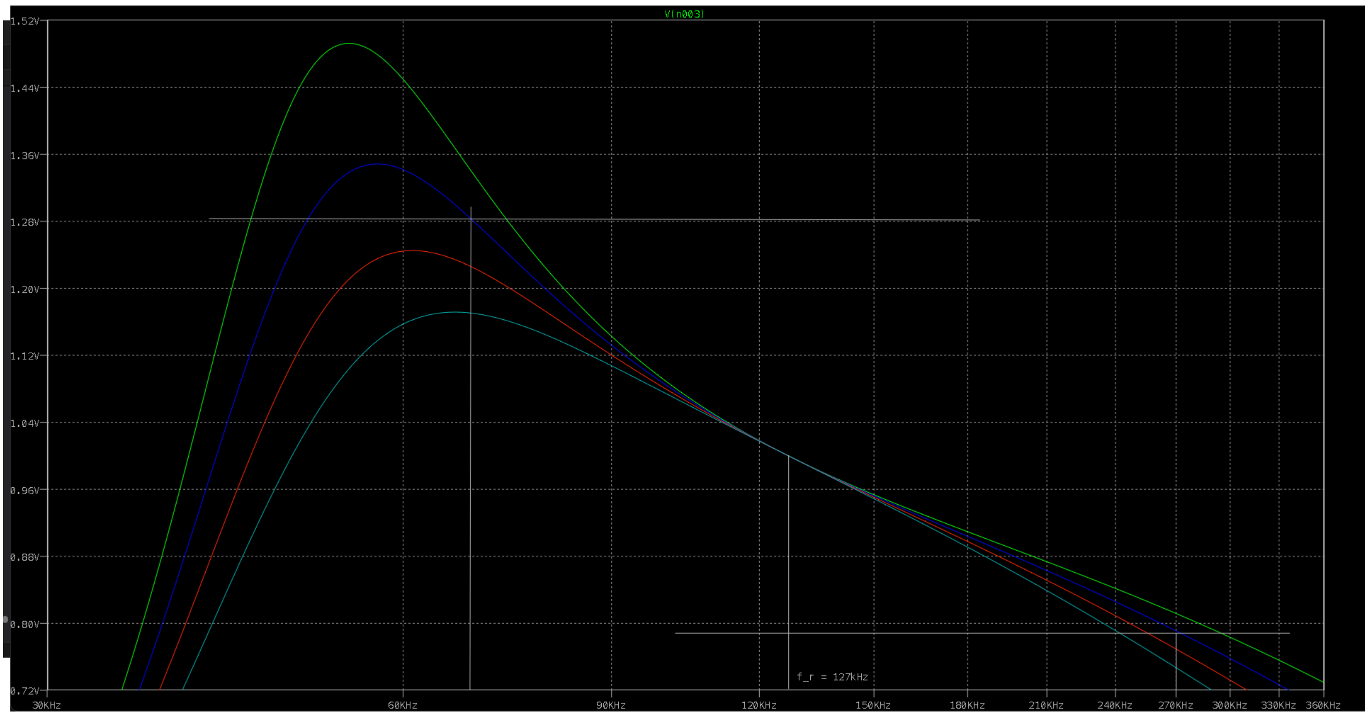

Figure 5.24: Output of the frequency-gain curve plotter

We can add horizontal lines as to the required gain and see the cut-off frequencies for the LLC operation between our desired gain range.
This stpe is crucial because we don't want to operate the converter at very high frequencies, because switching losses increase with the increase in switching frequency. We don't want to operate at lower frequencies because then the output voltage ripple will be higher and we don't want that either.
Hence we need to fine-tune the resonant component values to get the optimal graph at the optimal switching frequencies which is easy to control, is less sensitive to noise, and has the required gain as well.

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

I was given the task to design an LLC Converter as per the following specifications:

- Input Voltage to LLC (From PFC) = 400V DC (with 10V ripple)
- Output Voltage Range = 42V - 65V DC
- Output Power = 1.8kW

Here's a step-by-step process of how I designed the LLC:

5.6.1 Transformer Turn Ratio

The turn ratio of the transformer is given by the ratio of number of turns on the primary side, and the number of turns on the secondary side, i.e., n_1/n_2, where,
n_1 is the number of turns at primary side,
n_2 is the number of turns at secondary side.

Let $n = n_1/n_2 =$ transformer turn ratio, $M_g =$ gain of LLC
We know that,

$$n = M_g * (\frac{V_{in_{nom}}}{V_{out_{nom}}}) * (\frac{1}{2})$$

Where,
$V_{in_{nom}}$ = Nominal Input Voltage = 400V DC
$V_{out_{nom}}$ = Nominal Output Voltage = 52V DC
M_g = Gain of LLC = 1 (unity) ; We take it as 1 for this calculation since we want our converter to operate at resonance at nominal output voltage.
We multiplied by $1/2$ because we are using a half-bridge configuration.
Therefore,

$$n = 1 * (\frac{400}{52}) * (\frac{1}{2}) = 3.846$$

5.6.2 LLC Gain

Now we need to calculate the maximum and minimum gains that we require for our LLC converter. These gain values are calculated W.R.T. the nominal output voltage.
$V_{out_{min}} = 42V, V_{out_{max}} = 65V$
$V_{in_{nom}} = 400V, V_{in_{min}} = 390V, V_{in_{max}} = 410V$ (PFC Output)
Since,

$$V_{out} = V_{in} * (\frac{1}{2}) * M_g * \frac{1}{n}$$

We get,

$$M_g = 2n * \frac{V_{out}}{V_{in}}$$

Hence,

$$M_{g_{min}} = 2n * \frac{V_{out_{min}}}{V_{in_{max}}} = 2 * 3.846 * \frac{42}{410} = 0.788$$
$$M_{g_{max}} = 2n * \frac{V_{out_{max}}}{V_{in_{min}}} = 2 * 3.846 * \frac{65}{390} = 1.283$$

So, we need the gain of the LLC to be between 0.788 and 1.283

5.6.3 Equivalent Resistance

Next step is to calculate the equivalent resistance of the transformer, the rectifier circuit and the load resistance as per the FHA method (First Harmonic Approximation)
We require this step as we are replacing the non-linear part of the circuit with an equivalent resistor across the LLC such that the loading of the resistor is same as that of the non-linear part.
We know that,

$$R_{ac} = (\frac{n_1}{n_2})^2 * \frac{8}{\pi^2} * R_L$$

Also, $R_L = \frac{V_{outnom}^2}{Power} = 1.502\Omega$
Hence,

$$R_{ac} = 3.846^2 * \frac{8}{\pi^2} * 1.502 = 18.03\Omega$$

5.6.4 Choosing value of m

I will be using a value of m = 6.5 (because we can take any value between 6-10 generally and then we can design our system accordingly).
Here is a video that explains the effect of changing m. (Ctrl / Cmd + Click)
Basically, m is the ratio of the magnetizing inductance to the leakage inductance of the transformer.
A lower value of m will have much more gain at a particular frequency considering everything else is kept constant, while a larger value of m dampens the frequency - gain curve. (Figure 5.25)

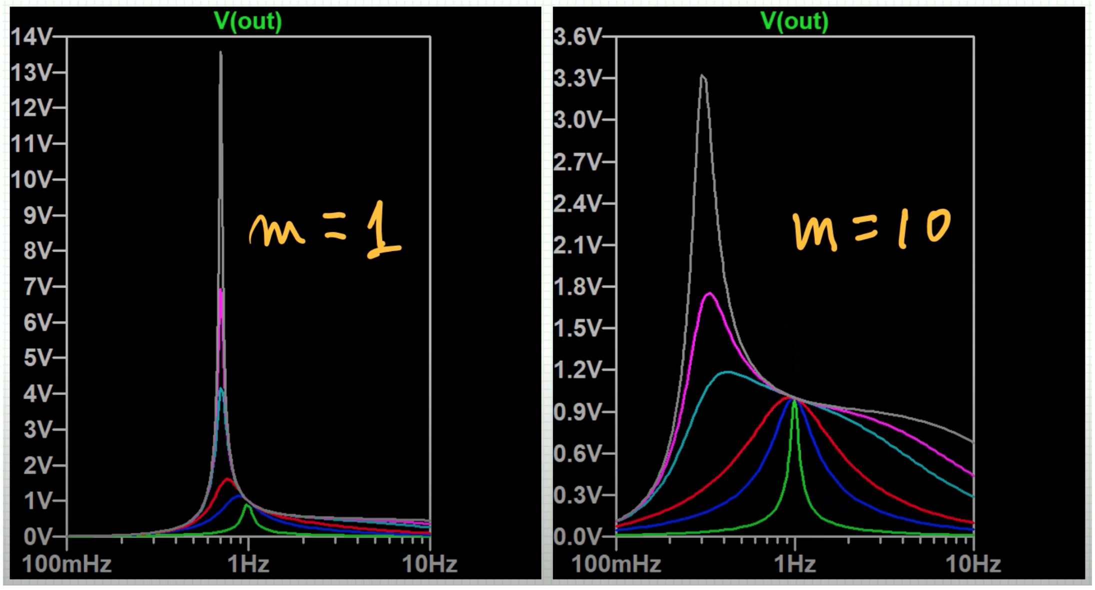

Figure 5.25: Effect of m on Frequency-Gain Curve

Note: This is a starting point our design. Later on, after other values such as L_r, C_r etc. are calculated, we can tune this value further as per our requirements to either minimise losses and hence improving efficiency, or get more gain from the LLC tank.

5.6.5 LLC Values

As per the given values, (assuming $f_r = 127kHz$ because that is the same frequency that we use for 110V system and usually a resonant frequency for LLC is taken between 100-150kHz) the frequency – gain curve according to this setup is as follows (Figure 5.26):

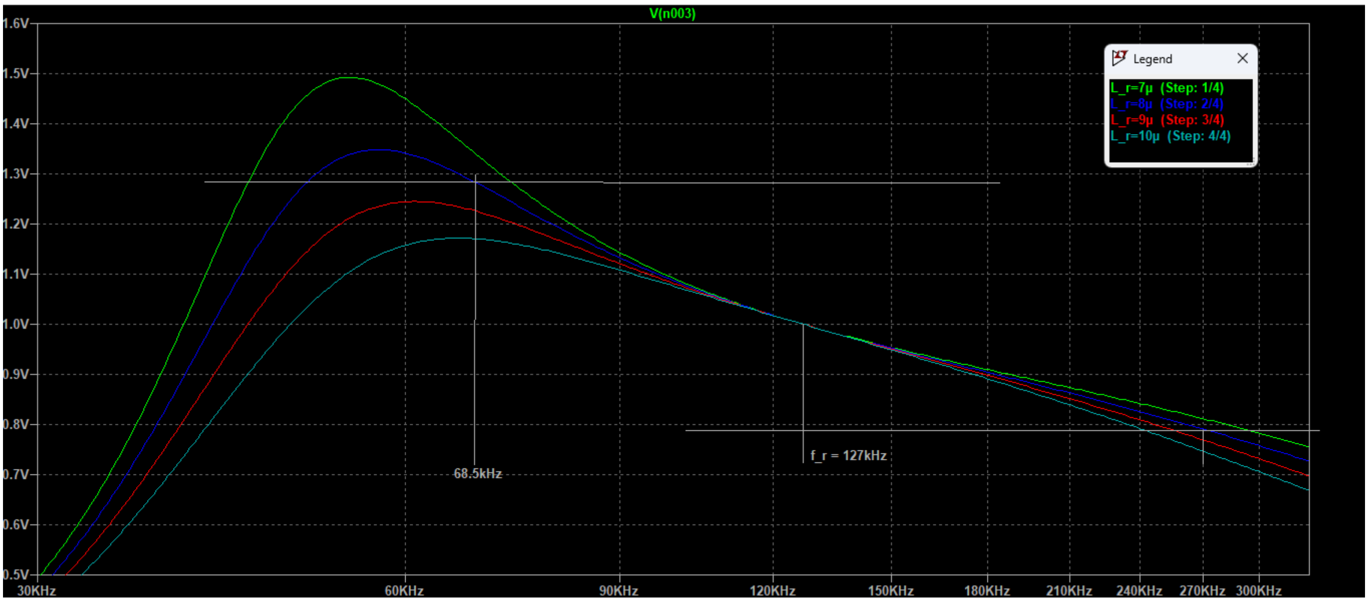

Figure 5.26: Gain-Frequency Plot for 48V-1.8kW LLC Converter

- The upper horziontal line represents the maximum gain of 1.283
- The lower horziontal line represents the minimum gain of 0.788
- The vertical lines at the intersection of the horizontal lines with the curve represent the maximum and minimum operating frequencies of the converter respectively.

As per the graph, L_r values more than $8\mu H$ are of no use as they do not reach the maximum gain that we require.
Hence a value of $L_r = 8\mu H$ is chosen. (We can also go for $L_r = 7\mu H$ if we wish to have some room for more gain, but theoritically, $8\mu H$ is the most optimal value with the given conditions and our chosen value of $m = 6.5$)
The operating frequency of the converter is from $68.5kHz$ to $270kHz$. We can calculate the remaining values of the LLC tank from the equations mentioned in Figure 5.23.

5.7 Calculation of Transformer for 110V - 3kW Specification

While testing and analysing the 110V - 3kW LLC converter, I noticed that the maximum heat was generated in the transformer (with temperatures rising upto 80°C at maximum load)
I thought that, if we can redo the calculations for the transformer, making the design more efficient, we can reduce the heat generated in the transformer.
In the current version, we are using the EE55/28/21 core with N87 material for the transformer.
I did some research, and finally decided to use the PQ40/40 core with PC47 material for the transformer.

5.7.1 Specifications of PQ40/40 Core

From the datasheet, and magnetics data:

- Effective Magnetic Path Length : $102mm$
- Effective Cross-Sectional Area : $201mm^2$
- Effective Core Volume : $20500mm^3$
- AL Value: $4300nH/turn^2$

- Core Window Area : $326mm^2$
- MLT value = $83.9mm$
- Relative Permeability = $\mu_r = 2300$
- Dimensions: A1: 40.5 mm, A2: 28.0 mm, B: 37.0 mm, øC: 14.9 mm, 2D: 39.75 mm, E: 28.0 mm, 2H: 29.5 mm (Figure 5.27)

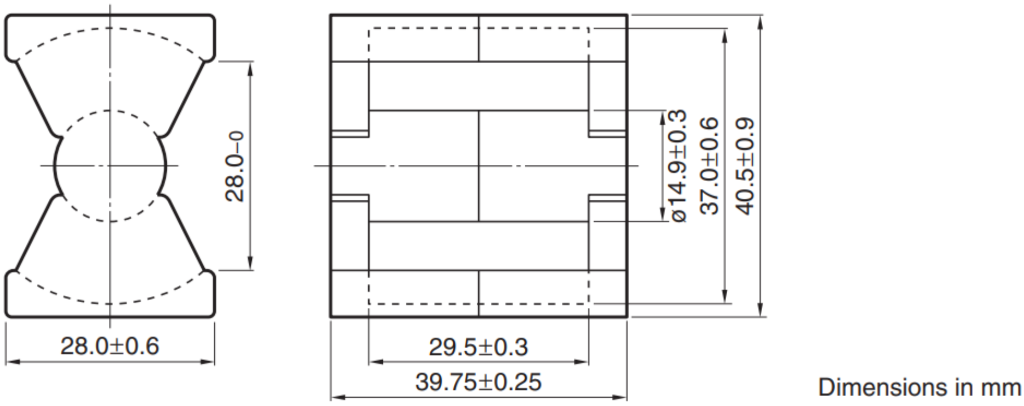

Figure 5.27: Cross-Section View of the PQ40/40 Core

5.7.2 Why PQ40/40 Core?

- **Power Handling Capability:** The PQ40/40 core has a large cross-sectional area ($2.01cm^2$) and a substantial window area ($2.50cm^2$), which allows it to handle higher power levels efficiently.
- **Magnetic Shielding:** PQ cores provide better magnetic shielding compared to other core shapes like EE or ETD cores. This helps in reducing electromagnetic interference (EMI) propagation, which is beneficial in high-frequency applications like our LLC converter.
- **Thermal Management:** The large core size of PQ40/40 allows for heat dissipation, which is important for maintaining thermal stability in air-cooled designs. This helps in managing the heat generated due to core and winding losses.
- **Mechanical Stability:** PQ cores are known for their mechanical stability and robustness, which is advantageous in applications where the transformer might be subjected to mechanical stress or vibrations.

5.7.3 Material Selection: PC47 Ferrite

- **Low Core Losses:** PC47 material exhibits low core losses at high frequencies, which is essential for maintaining high efficiency in our LLC converter. At 100kHz and 200mT, the core loss is 250 kW/m³ at 100°C, which is lower compared to other materials like PC40 and PC44.
- **High Saturation Flux Density:** PC47 has a higher saturation flux density (530 mT at 25°C and 420 mT at 100°C) compared to other ferrite materials. This allows the core to operate at higher flux densities without saturating, which is beneficial for handling the power levels in our application.
- **Wide Frequency Range:** PC47 is optimized for a wide frequency range (10 kHz to 500 kHz), making it suitable for our LLC converter that operates at a resonant frequency of 127 kHz and can vary from 70 kHz to 300 kHz.

- **Thermal Stability:** PC47 material maintains its magnetic properties over a wide temperature range, with a Curie temperature above 230°C. This ensures stable performance even under varying thermal conditions, which is important for air-cooled designs.
- **Cost-Effectiveness:** While PC47 material offers superior performance, it is also cost-effective compared to other high-performance ferrite materials. This aligns with our requirement for an optimal design that balances performance and cost.

Taking into account the above-mentioned reasons, subsequent calculations for the following parameters were performed:

- Primary Inductance (L_p) and number of turns at primary winding (N_p)
- Inductance at Secondary Winding and (L_s) and number of turns at secondary winding (N_s)
- Power Handling Capability of the Transformer
- Required Air Gap to get precise Inductance values.
- Wire cross section area for primary and secondary windings (A_p and A_s)
- Litz Wire Calculations (For $\delta = 0.1mm, 300kHz$ the strand diameter was calculated to be 32AWG (0.2mm))
- Number of strands required for primary and secondary windings ($N_{strands,P}$ and $N_{strands,S}$)
- Winding lengths for primary and secondary windings (L_P and L_S)
- Winding Volume for primary and secondary windings (V_P and V_S)
- Winding Height Calculation

The transformer design for the LLC converter using the PC47PQ40/40Z-12 core was expected to meet the specified requirements, with the calculated winding height being within the maximum winding height of 29.5 mm for the PC47PQ40/40Z-12 core, ensuring that the windings will fit within the core window area. The design considered the high-frequency operation, power rating, and the need for minimizing losses, providing a robust solution for the intended application.

5.8 PCB Design

There was another project ongoing in the company (Design of a Remote Monitoring System).
It is separate device that is connected to the inverters etc. that our company sells that can be used alongwith the inverter to remotely monitor the status and statistics of the inverter.
The device is connected to the inverter via RS485 and sends the data to the cloud via 2G/4G Modules (Quectel Modules).
Earlier, the design was outsourced to a third party, but the company decided to do it in-house.
I was given the task to design the PCB for the Remote Monitoring System.
I used Altium Designer and make the schematic (Figure 5.28) and PCB Layout (Figure 5.29) for the same.

- Easy availability of components
- Cost of components
- Size of the PCB
- Manufacturability (2 layer)
- Track width for power tracks
- Differential signal routing for high speed communication
- Mounting holes
- Scope for changes in the circuit

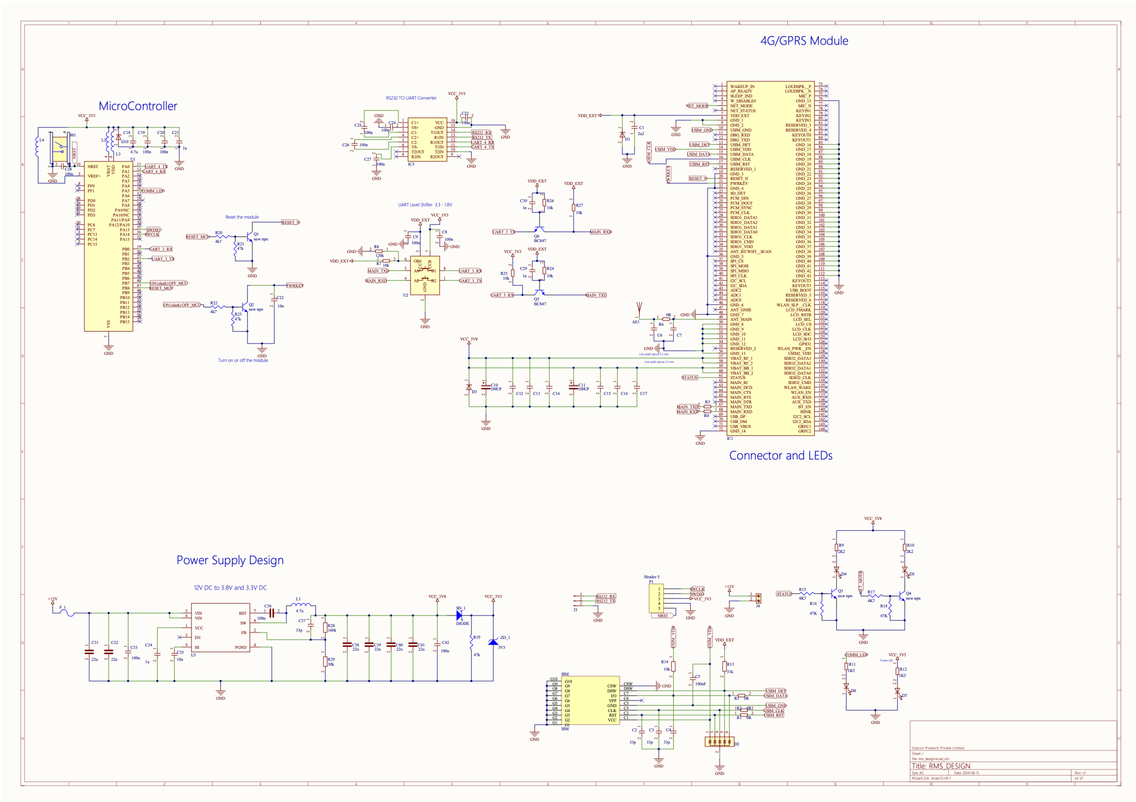

Figure 5.28: Schematic of the Remote Monitoring System

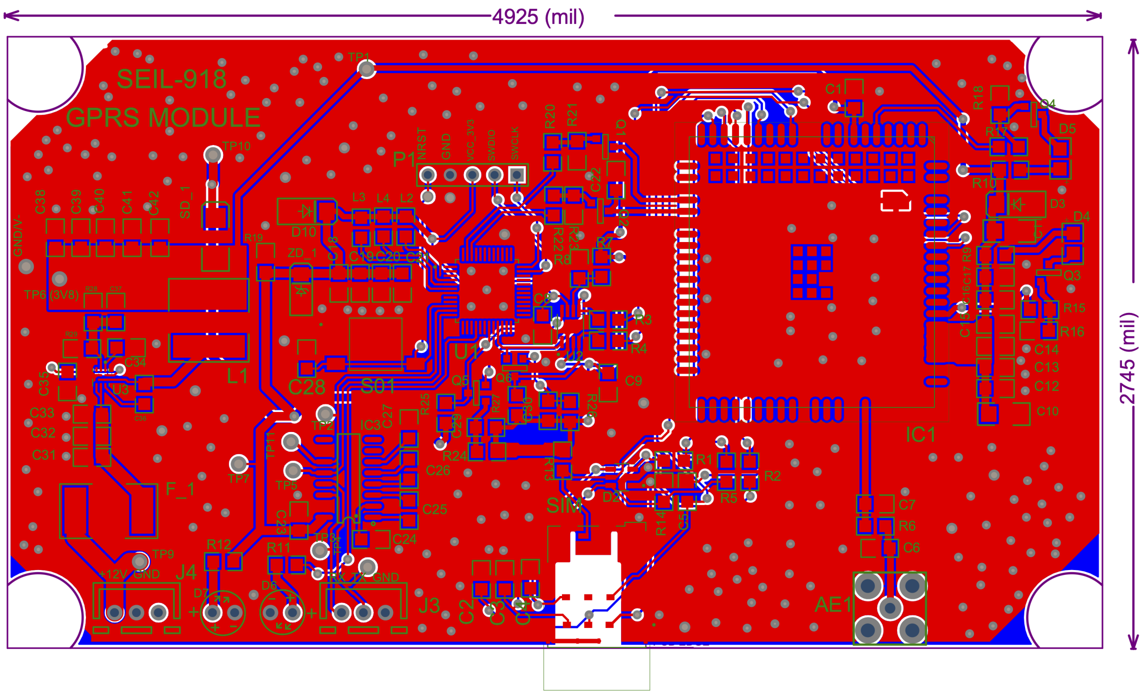

Figure 5.29: PCB Layout of the Remote Monitoring System

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.

7. References

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