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Design and Analysis of Gallium Nitride-based LLC Resonant DC-DC Converter

by

Amrit Ghimire

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Design and Analysis of Gallium Nitride-based LLC Resonant DC-DC Converter

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CERTIFICATE OF APPROVAL

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled "**Design and Analysis of Gallium Nitride-based LLC Resonant DC-DC Converter**" submitted by Amrit Ghimire in partial fulfillment of the requirements for the degree of Master of Science in Power Electronics and Drives Engineering.

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ABSTRACT

This thesis presents the design and analysis work of an isolated LLC (Resonant Inductor, Magnetizing Inductor, and Resonant Capacitor) resonant DC-DC. It includes a Power Factor Correction (PFC) converter unit and an LLC Resonant topology DC-DC converter. A single-phase 220 Volts 50 Hertz power is supplied to the critical boost PFC unit, which rectifies and boosts the voltage level to 400 Volts DC output, which is supplied to the DC-DC converter where a half-bridge inverter modulates it to a square-wave signal with a frequency of 110 kHz. The alternating signal is passed through the LLC resonant network in combination with the High Frequency Transformer (TFT). The primary of the transformer is connected with the LLC filter, and the secondary side is connected with the rectifier circuit and to the output terminal, which records a filtered DC output voltage of 13.148 Volts.

The emerging revolutionary semiconductor Wide Band Gap (WBG) device Gallium Nitride (GaN), GS16616T, is implemented as a switching device in a half-bridge inverter circuit whose operating voltage is 650 Volts, very high switching frequency (in the MHz range) and good thermal performance. The half-bridge inverter is utilized to facilitate natural Zero Voltage Switching (ZVS), which helps to reduce the switching loss, enhances the power density of the converter, and, above all, enhances the efficiency of the converter. GaN-based switching converters result in a superior substitute for traditional converters using silicon-based switches. This design and the simulation work (in LTSpice software) attained a peak efficiency of 95.887% while utilizing GaN switches in the converter at a resonating frequency of 110 kHz, whereas efficiency for the Silicon-based converter was found to be 94.59 %, with the improvement of efficiency by 1.288%, which is 56.8% switching loss reduction in the GaN-based converter.

Keywords: LLC Resonant Network, DC-DC converter, High Frequency Transformer, High Power Density, Wide Band Gap Devices, Gallium Nitride.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2DEG	Two-Dimensional Electron Gas
AC	Alternating Current
CCM	Continuous Conduction Mode
DC	Direct Current
EMI	Electromagnetic Interference
EVCS	Electric Vehicle Charging Stations
HFT	High Frequency Transformer
HEMT	High Electron Mobility Transistor
IGBT	Insulated Gate Bipolar Transistor
LTSpice	Linear Technology Spice (Simulation Software)
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PFC	Power Factor Correction
THD	Total Harmonic Distortion
LLC	Magnetizing Inductor Secondary Inductor Capacitor
WBG	Wide Band Gap
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

CHAPTER 1: INTRODUCTION

1.1. Background

There is elevated use of power electronics converters in different applications, like consumer electronics, the automotive industry, telecommunication systems, renewable energy systems, aerospace and defence, and data centers. One of the emerging and widely growing applications of power electronics converters is in Electric Vehicle Charging Station (EVCS). Electric Vehicle adaptation is contributing well to controlling carbon emissions, reducing pollution, and helping to reduce noise pollution in urban areas. The electric vehicle application has many advantages over internal combustion vehicles, and they are considered environmentally friendly and energy-saving. According to Bloomberg, Sales of EV cars may increase to 28 million in 2030 and 54 million by 2040 [1]. By 2030, Nepal has targeted sales of EVs to cover 90% of the market of all private EV sales[2]. As per the data from the Nepal Electricity Authority, the daily average consumption of electricity for charging electric vehicles is 36,666 kWh of energy. The data also shows a total of 724 charging stations installed, including governmental as well as private investment, and 238 of them are under construction and total installed capacity of 78.8 MW chargers is installed. The data is shown in Figure 1.1[3]. This signifies that there is an abrupt need for technological adaptation of the descent electric vehicle charging technology to cooperate with the increasing demand in the field, enhance reliability, efficiency, reduce losses in the system, and for long-term economic benefits. A huge investment and progress are going on in the field of charging technology. Real-time charging management is required to ensure rational reliability, efficiency of the electrical systems, and economics of the electricity services.

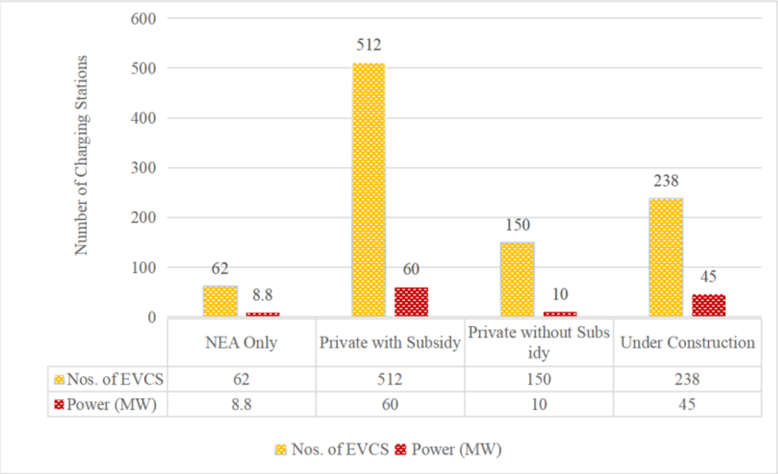

Figure 1.1: Status of Electric Vehicle Charging Stations in Nepal

With the accelerating proliferation and active penetration of electric vehicles (EV) globally as well as in the Nepali market, the significance of descent charging technology and infrastructure is increasing along with the requirement of higher efficiency and high-power density devices. Furthermore, with the increased demand for fast charging to reduce range anxiety and long charging time, the demand for good charging technology has increased [4]. The sudden automotive market shift from internal combustion (IC) engine locomotives to electric vehicles has considerable economic, environmental, and ecological benefits due to cost-effectiveness and net-zero carbon emissions.

This report discusses the design of PFC converter, LLC Resonant DC-DC Converter, and their analysis and application in various emerging fields where it can be implemented, with better efficiency and compatibility. This process involves the design of an improvised noiseless critical boost Power Factor Correction (PFC) unit along with DC-DC converter design, which assists in generating the required output voltage level to charge the rated batteries safely and with a desire for high reliability. A boost PFC circuit is designed to convert the available AC source in residential distribution to a DC source acting as a rectifier, increasing the voltage to the required voltage level and helping to enhance the power quality by reducing Total Harmonic Distortions (THD) and Electromagnetic Interference (EMI). DC-DC converters improve safety and efficiency through an isolated topology, allowing bidirectional energy flow during charging and the regeneration braking process. Most importantly, the converter works to maintain a filtered output voltage profile, ensuring high efficiency and reliability of the charging system[4]. A 220 Volts Alternating Current (AC) from a residential power supply is connected to the critical boost PFC converter, which rectifies the AC signal and boosts the voltage level to 400 Volts. The output of PFC is fed to the half-bridge inverter of the isolated LLC resonant DC-DC converter, which ultimately reduces the voltage level to 12 volts[5]. The charging of different vehicles uses batteries with different voltage levels. The block diagram of the overall DC-DC converter setup is illustrated in Figure 1.2. The research work focuses on the computation of output power, voltage profile, switching losses, overall losses, and efficiency of the converter. This involves a computation of the parameters using conventional power semiconductor devices, Silicon-based MOSFETs, and with revolutionary wide band gap Gallium Nitride switches, and the performance is compared with each other, and a better resolution in Gallium Nitride is looked for.

A half-bridge inverter with Gallium Nitride (GaN) as a switching device is used in the first stage to convert the DC voltage into a high-frequency AC signal generation, which is further transferred to the rectifier circuit through an isolated high-frequency transformer to convert back to the DC required voltage level[6].

Revolution is going on in the power electronics sector by the emergence of Wide Band Gap (WBG) devices such as Gallium Nitride (GaN) and Silicon Carbide (SiC) as cutting-edge semiconductor devices with superior thermal performance, higher operating voltage, very high switching frequency, low on-state resistance and minimum reverse recovery power. It creates a possibility for highly efficient, compact design and futuristic energy conversion technologies in power electronics. Gallium Nitride (GaN) has high electron mobility for low on-state losses, high frequency switching in the range of megahertz, and a normal operating voltage of 650 volts and switching frequency in the range of megahertz. GaN transistors are also recognized as GaN HEMT (High Electron Mobility Transistor)[7]. Silicon Carbide (SiC) is another WBG that operates at a high voltage of 1,200 V and 300 kHz switching frequency. It performs exceptionally well thermally and efficiently in high-power applications (such as in MW-scale converters). Compared to conventional Si-based semiconductor devices, Wide Band Gap (WBG) semiconductor devices have good improvement in reliability, compact designs, and reduction in energy losses. And, due to the mentioned cutting-edge attributes, a Gallium Nitride-based semiconductor device is proposed for this application to design a highly efficient compact design with higher thermal management specifications.

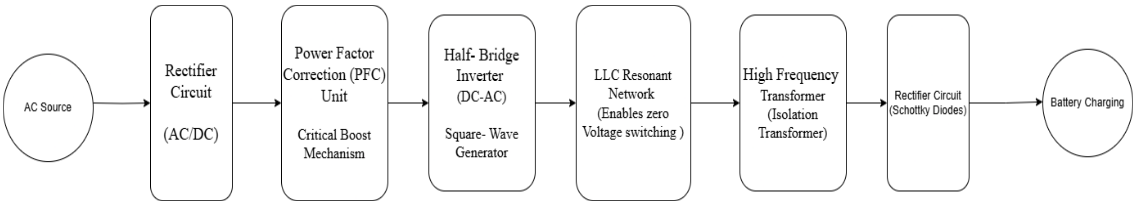

Figure 1.2: Block diagram of the overall DC-DC converter system

1.2. Problem Statement

The latest power semiconductor switches implemented in power electronics applications like renewable energy sources, electric vehicle charging stations have moderate efficiency and high losses. The primary challenge is to manage the good efficiency of the converter along with its compact design structure, providing high power density and consequently thermal management properties of the converter. There is high switching loss in high-frequency operational switches, and heat radiation is high, which leads to the requirement of larger-sized heat sinks, resulting in the reduction of power density of the charger converter.

This points out that the conventional silicon-based switches being implemented in the converters have significant issues. Eliminating those issues is essential to enhance the power quality, reduce losses, enhance efficiency, and reliability of the system, and assist in saving the economy by reducing the electrical losses in the system.

1.3. Objectives

The primary objectives of the research work are as follows;

- To reduce the switching losses across the GaN switches.
- To enhance the efficiency of the converter.
- To compare the outcomes of gallium nitride (GaN) and silicon-based power converters.

1.4. Scope of Thesis

The following are the major scopes of this thesis, including technical, financial, and environmental benefits of the proposed converter topology.

- Enhancement in efficiency and thermal performance with higher operating temperatures and lower switching losses.
- Reduces size and weight by minimizing passive components (Capacitors and Inductors in the filter circuit), increasing power density, and lowering operational costs.
- Enables ultra-fast switching, reducing energy losses and improving the power density of the converter by reducing the size.

1.5. Outline of the thesis

The following is an outline of the thesis report:

Chapter I: Introduction section discusses the growing usage of power electronics converters in different applications. The scenario of power converters utilized in the electric vehicle charging station in the global and Nepal’s context is highlighted. The benefits of using GaN as a switching semiconductor device in the converter.

Chapter II: Literature Review discusses the scenarios, background, and latest research and development works conducted by researchers by the use of GaN as a switching device in the DC-DC converter topology. This section also covers the technology and general practices in the field of power electronics and DC-DC converters, the possible research gaps in this arena, and proposed solutions for optimised charging technology with the use of wide band gap switches.

Chapter III: Methodology illustrates the approach to the use of GaN switches and analyzes the behaviour of the converter's operability, loss analysis, and efficiency. It also explains about the efficiency at the resonating frequency, exploring the resonant frequency along the LLC Resonant Network. Design framework of PFC Converter, LLC, Resonant Network, along with DC-DC Converter. Moreover, losses associated with silicon-based converters and Gallium nitride-based switches are compared.

Chapter IV: Results and Discussion focuses on the results of the losses across all the switches (GaN switches and Schottky diodes), losses across the overall converter, and the efficiency of the converter. The efficiency enhancement results are validated with the results in the descent reference papers. This section discusses and analyses the achievement of enhanced efficiency and reduced losses at resonating frequency, and an improved nature from comparison with the performance of the conventional converter.

Chapter V: Conclusion discusses the summary of the works performed along with the obtained outputs, switching losses, efficiency, and power rating. This section concludes with the disadvantages of using conventional Si-based switches and the benefits of using GaN switches. Present and future aspects of the thesis work are also added.

1.6. Limitations of the thesis

The challenges and the limitations that were encountered during the thesis period are discussed below;

- The research is simulation-based, with limited access to real-world input, output, and loss data due to the unavailability of GaN switches in the local market.
- High-frequency switching may introduce EMI and parasitic effects, necessitating advanced filter circuits and detailed optimization techniques.
- GaN semiconductor devices are cutting-edge technology, but aren’t locally available and are higher cost compared to conventional power semiconductor switches.
- Economic, political, and environmental factors that may influence the research context and its applicability are not discussed.

CHAPTER 2: LITERATURE REVIEW

2.1. Overview

The application of power converters in various fields of power electronics has undergone a significant evolution over the past few decades, taking an interleaved step in development. A major, remarkable step is taken in the field of electric vehicle charging station development and extracting energy from renewable energy sources. Considering the scenario of electric vehicle charging converters, early charging systems primarily relied on silicon (Si)-based power devices due to their established market popularity and cost-effectiveness. Historical studies have shown that Si-based converters, although robust, typically achieved conversion efficiencies in the range of 90–93% under moderate power levels, with switching frequency limitations of around 100 kHz. There was a common practice of using huge heat sinks and large converter sizes for thermal management. EVCS converters that are commonly implemented in Nepal and most countries are Silicon-based. But few countries have already started using wide band gap (WBG) semiconductor power switches, which have recently been discovered with high conductivity, fast switching frequency, and good thermal management.

As per the report generated by NEA, Nepal's EV charging infrastructure, driven by both NEA and private sector investments in total has 724 charging stations and a total installed capacity of 78.8 MW. Nepal is constantly progressing in electric vehicle infrastructure development[3]. The losses normally occurring with conventional technology seem to be 7-10 % of the total power. Utilizing the GaN-based converter in the developing phase could be beneficial to save on electrical losses, safety precautions, and repair and maintenance, along with ease from a consumer perspective for good and fast services.

In recent years, the advent of wide bandgap semiconductor devices, specifically Gallium Nitride (GaN) and Silicon Carbide (SiC), has marked a paradigm shift in the semiconductor market since their discovery as drastically revolutionizing semiconductor power devices. They are now found to be truly advantageous in EV charging technology. GaN-based converters have benefits in higher electron mobility, enabling operation at very high frequencies up to 1 MHz, and offer efficiency improvements that can boost overall system efficiency to as high as 96–97%. Additionally, GaN devices reduce switching losses by 60–70%, allowing for more compact designs and lower cooling requirements. Similarly, SiC-powered devices excel in high-voltage and high-power scenarios, demonstrating power densities that are 2.5 times higher than traditional Si outputs and operating at junction temperatures exceeding 200°C. The future of power electronics converters for charging systems and other applications, with enhanced efficiency, reduced size, and improved thermal performance, is critical to meeting the demands of fast and reliable charging infrastructure and the renewable energy market[8].

2.2. Wide Band Gap (Gallium Nitride)

Wide Band Gap (WBG) Devices are semiconductor devices that are made from materials with a higher energy gap between valence band and conduction band in the atom in comparison with traditional Silicon (Si) based semiconductors. These WBG devices are Silicon Carbide (SiC) and Gallium Nitride (GaN), which have an energy bandgap of around 3.3 eV and 3.4 eV, respectively, while Silicon has a bandgap of 1.1 eV. The materials in these devices enable them to operate at higher voltage levels (up to 10 kV range), have elevated operating temperature limits (200–300°C), and can attain a very fast switching frequency (up to MHz range)[9].

Initially, the super-junction MOSFET at the earliest stage of discovery was a popular version of semiconductor, as it was built by changing one directional current flow to two-dimensional flow, vertical to vertical and horizontal flow. In such super-junction diodes in this condition, a combination of two hetero junctions of p-drift region and n-drift region. When both designs are combined, the field distribution is found to be uniform, and a drastic increase in breakdown voltage. But as the breakdown voltage increased, the on-state resistance increased, so to trade off, the doping concentration was increased by about 10 times. On the principle of super junction-diode, various design features aimed at reducing power losses and improving thermal performance, making it suitable for a wide range of power electronics applications. Here, the doping concentration of the n-drift region is to be made ten times higher than classical power MOSFET.

The GaN HEMT has a structure of heterojunction formation between the Aluminium Gallium Nitride (AlGaN) Barrier and Gallium Nitride Buffer layer. A phenomenon called two-dimensional electron gas (2DEG) is naturally induced in this layer, which is extremely high mobility of electrons with low scattering, allowing electrons to move with rapid speed across the channel. This mobility contributes to reducing conduction losses and enhancing efficiency. The turning on and off of the switch is controlled by applying voltage to the gate terminal. When a positive voltage is applied to the gate terminal, it attracts electrons and promotes 2DEG, allowing the flow of current between the source and drain. Conversely, applying a negative voltage or reducing the voltage depletes the electron density in a channel and reduces current flow. GaN HEMT also features very low gate charge and low parasitic capacitances. These attributes lead to extremely fast switching speed, and rapid transition reduces the switching period, thus reducing the energy lost in each transition. This enhances the reduction of conduction and switching loss and enhances efficiency[9].

Gallium Nitride was quite a familiar material to us as it is being used in energy-efficient LED lights, Blu-ray players, and in power-efficient military/ aeronautical systems like radar for a long time. And after finding its peculiar behaviour, these devices are now applicable in power electronics applications such as electric vehicle charging converters, solar inverters, data center converters, aerospace systems, and the converters used in them, and even in fast chargers for cell phones, which are widely available now in the market. And WBG devices are capable of creating this demand and enthusiasm due to their ground-breaking performance, specifically due to their high thermal stability, low energy losses, and high efficiency[10].

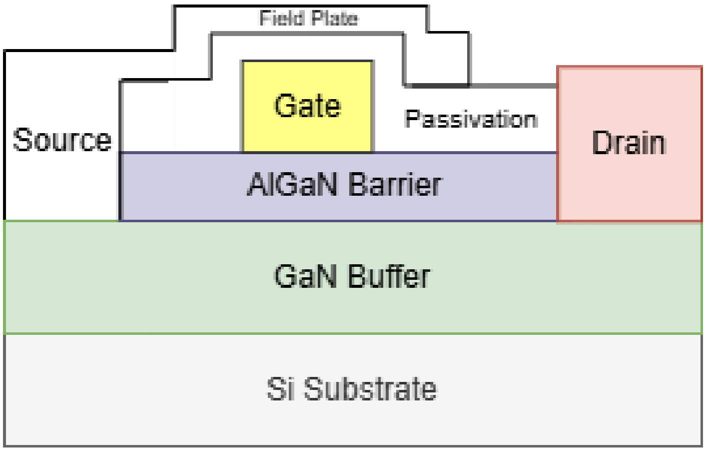

Figure 2.1: Internal structure of Gallium Nitride HEMT switch

The Gallium Nitride devices are typically used for medium voltage applications, as they deal with voltage levels of around 600 volts and higher switching frequencies. Commercially, GaN switches of 650 Volts are available in the market from companies like Infineon, Wolfspeed, etc. Figure 2.1 illustrates the schematic diagram of the internal structure of the Gallium Nitride switch. Its heat radiation resistance and eco-friendly nature help in reducing energy usage and pollution, and recently, they are being recognized as a semiconductor for next-generation chips and power electronics circuits, and are called "Ultimate Semiconductor Material”[11].

2.2.1 GaN-based semiconductor switches

This project is mainly focused on the implementation of wide band gap devices (Gallium Nitride) with their superior properties, such as a high operating temperature limit. Robust and high performance with the following major properties.

I. Low on-state Resistance:

This enables the converter to reduce conduction losses, critical for high-frequency operation. This is the property of the material that at the time of switch operation conduction process is more efficient due to this.

II. High Switching Frequency:

This enables very high switching frequency operation in the range of megahertz. It helps to reduce the size of the magnets and capacitors, and other passive components in the device, enhancing the power density. As switching frequency is directly associated with switching loss, it should incorporate higher losses, but due to the two-dimensional gas formation methodology of the electron in conduction mode doesn’t increase the losses as expected.

III. Zero Reverse Recovery Charge:

This has a property to eliminate tail currents during switching operation, thus it helps in improving reliability. As there is no body diode present in the GaN switches, it can operate more quickly as there is no loss of power in the transition of states.

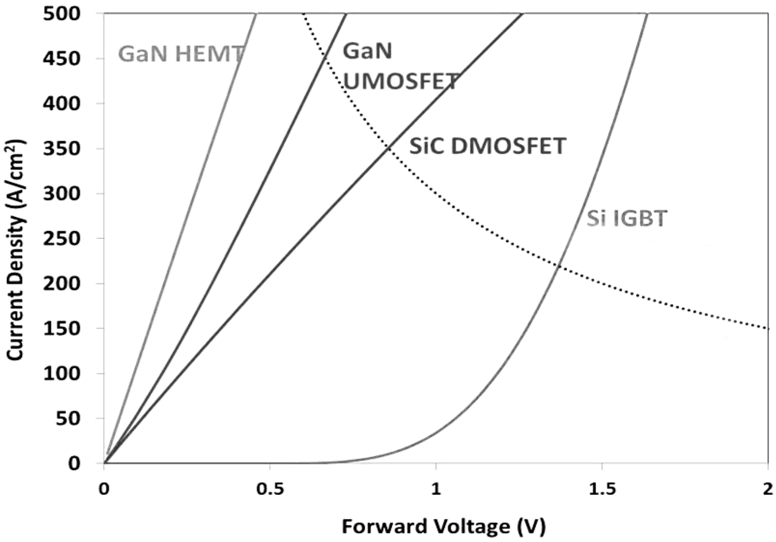

Figure 2.2: A comparative graph between Si, SiC, and GaN Current Density versus application of Forward voltage

This application uses a GaN model, GS66516T, from Infineon. Figure 2.2 illustrates the comparison of current density versus forward voltage among Si, GaN, and SiC semiconductor devices. This demonstrated the superior nature of wide band gap semiconductor devices for higher power, higher switching speed. The parameters shown for the Infenion GS66516T GaN switch are illustrated in Table 2-1.

Table 2-1: Infineon GS66516T Configuration

Parameter GS66516T	**Value**
Voltage Level	650 Volts
On Resistance	25 m Ohm
Maximum Drain-to-Source current	60 A
Drive voltage requirement	(o to 6 Volts)
Switching frequency (max)	10 MHz
Operating junction temperature	$-55^{\circ}\mathrm{C}$ to $+150^{\circ}\mathrm{C}$
Reverse Recovery Loss	0 Watts

Figure 2.3 illustrates the Nature of drain-to-source current versus drain-to-source voltage depending on the temperature range 25 °C to 150 °C[11]. And Figure 2.4 demonstrates the transient nature dependence on the thermal impedance [10].

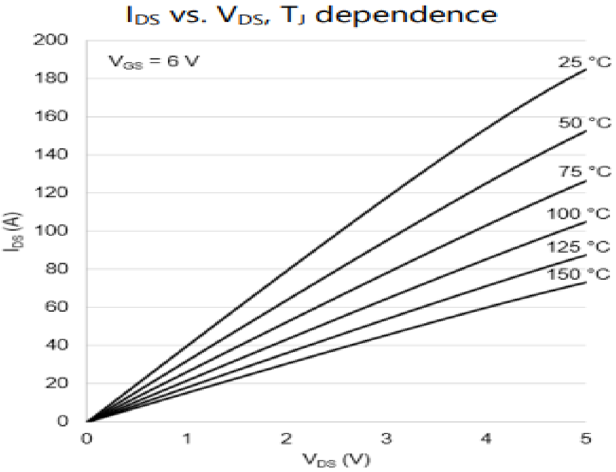

Figure 2.3: Nature of drain-to-source current versus drain-to-source voltage depending on the temperature range for GS66516T GaN switch

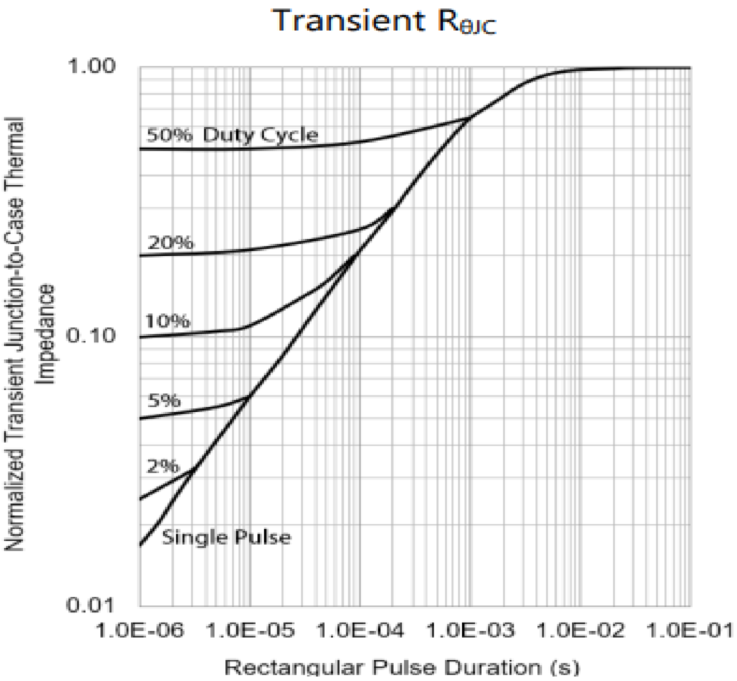

Figure 2.4: Transient nature shown by the GS66516T GaN switch in dependence on thermal impedance

2.3. Gate Driver Circuit

A gate driver circuit in the case of converter design is the most essential electronic circuitry that translates low-power control signals into high-amplitude power and high-current signals that are required to effectively turn on and off power semiconductor devices like MOSFETs and IGBTs. The major components involved in gate driver circuits are gate driver Integrated Circuits (ICs), bootstrap capacitors, gate resistors, decoupling capacitors, isolation techniques, and PCB layouts. The major functions of a gate driver circuit are signal translation, as it acts as a bridge between logic signals of the controller and the power switching devices, acts as a voltage and current amplifier, and adjustment of switching speed, and isolates the switches and high-power supply[12]. Such driver circuits are utilized in DC-DC converters, motor drivers, inverters, and renewable energy systems. The gate driver circuit avoids the gate ringing phenomenon and prevents damage to the power semiconductor switches. Figure 2.4 illustrates the control mechanism of the gate driver circuit controlling the switch operation.

The requirements of the gate driver circuit are mentioned as follows;

- Meet the voltage and current requirements of the gate emitter or source region.
- They act as an isolation between the source and gate terminal of the semiconductor switches.

- They can work with the floating supply (emitter).
- They work as high impedance inputs during sourcing and low impedance behaviour during sinking.

There are two types of isolated and non-isolated gate driver circuits. The isolated work in a greater voltage range of over 3000 Volts is designed for high safety. For high switching speed switches, they are implementable, and no ground potential difference occurs in the case of an isolated gate driver. In case of non-isolated, the operating voltage is up to 700 Volts. They are less safe than an isolated gate driver. There is a delay due to a high-side bulky circuit. Comparing the properties of isolated and non-isolated, isolated seems better for noise immunity, though they are costly and complex in design. In an isolated gate driver circuit, the commonly used methods are using optocouplers, in which fibre optic cables can be used for high-power converters. This increases the distance of isolation and the effects increase.

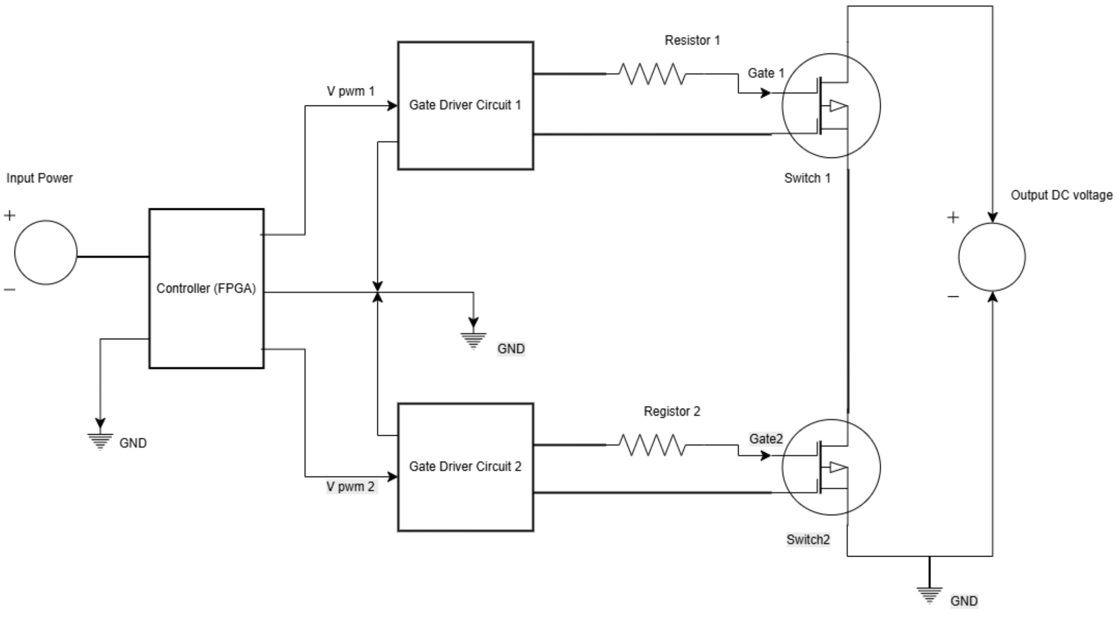

Figure 2.4: Circuit diagram of gate driver connected to switches

2.4. ZVS Operation

Zero Voltage Switching (ZVS) is a soft-switching technique where a power semiconductor device is turned on or off when voltage across its terminals is zero or near zero. This eliminates switching losses during the fast switching operation, whereas there is a high switching loss during hard switching. ZVS minimizes switching losses by ensuring the device voltage drops to zero before turn-on. The LLC resonant tank comprises the resonant inductor, magnetizing inductor, and resonant capacitor; the magnetizing current acts as a current source during dead time to discharge parasitic capacitance. GaN devices used in the application enhance ZVS due to their low output capacitance. ZVS eliminates voltage current overlap during turn-on, which is critical for high-frequency operation[13]. Low losses are also beneficial for designing compact designs of devices, along with reduced cooling requirements. Figure 2.5 demonstrates the advantages of zero voltage switching as ZVS is represented by soft switching, which took place during low current and low voltage profile, resulting in lesser loss, but hard switching shows higher loss in the system [14].

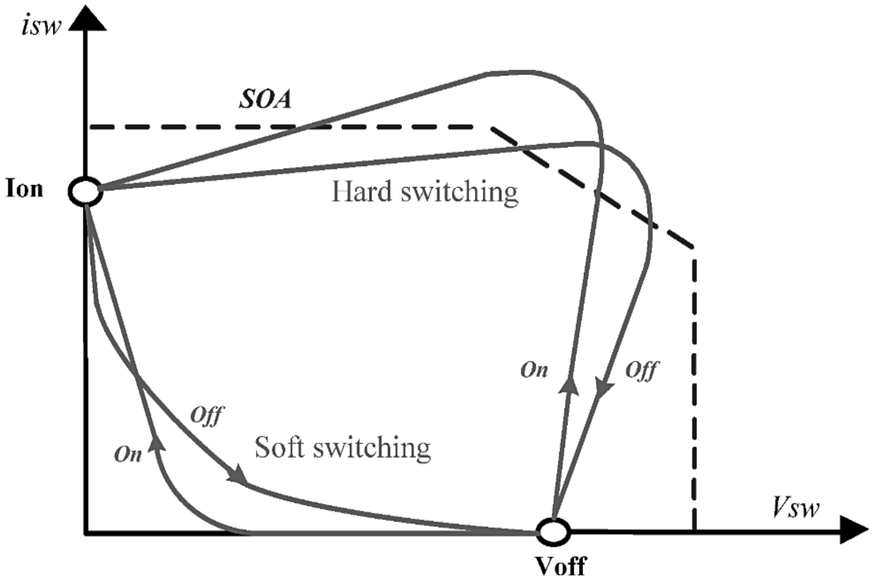

Figure 2.5: Representing soft and hard switching comparison between switching current versus switching voltage

2.5. Resonance Frequency

Resonance frequency is a fundamental concept in physics as well as in engineering. In electrical and electronic circuitry systems, resonance occurs in a circuit with an inductor and capacitor interaction, which signifies that at the resonant frequency, the inductive reactance is in equilibrium with capacitive reactance, which are in opposite phases. This leads to resistive behaviour of the circuit, allowing maximum flow of current through the circuit. This also signifies the presence of minimum impedance in the circuit. The resonant frequency is given by the following formula;

$$F_r = \frac{1}{2\Pi \cdot \sqrt{LC}}$$

where L is inductance in Henry (H) and C is capacitance in Farad (F), and F_r is is the resonant frequency. The concept is very important to implement in designing filter circuits, oscillators, tuning circuits, and LLC resonant converters. Especially, Gallium Nitride switches enable the converter to operate at higher frequencies, which leads to a reduction in the size of passive components and helps to enhance power density and efficiency of the system[15].

2.6. Power Factor Correction Unit

A power factor correction unit is an electronic circuit that is implemented in power electronic circuits to improve the power factor, enhance the power quality, and convert the AC supply into DC to ensure a filtered output voltage level. Power factor is the ratio of real power to the apparent power and it signifies the efficiency with which electrical power is converted to useful work. The PFC units are generally of two types, passive PFC units and active PFC units. A power factor correction unit is an electronic circuit. The ones with capacitors and inductors assembly are passive PFC units, and a few of the active PFC units are classified as follows[16];

2.6.1 Critical Boost PFC:

This PFC converter topology involves the operation of a boost converter at the edge of continuous conduction mode and discontinuous conduction mode, thus called a critical boost PFC unit. This mode helps to reduce conduction losses and reduce overall component stresses while maintaining a power factor near unity. This results in improved efficiency. This is the model implemented in the research study.

2.6.2 Totem Pole PFC:

The totem pole PFC involves a pair of active switches arranged in a totem pole configuration. This configuration and operation result in lowering conduction losses and faster switching, which improve the performance and power quality of the converter and are usually employed in rapid transient response operation.

2.6.3 Noiseless Bridgeless PFC:

The bridgeless PFC unit has a configuration with the replacement of the conventional diode bridge with active switching elements. This leads to a reduction in conduction losses and enhancement of efficiency, as well as minimizing the noise or electromagnetic interference (EMI) profile.

2.7. DC-DC Converter topology

DC-DC converters are fundamental power conversion devices that convert a ripple voltage (DC) input into a filtered and reliable output voltage. These converters consist of stages such as rectification, switching, isolation, and filtering to ensure the final power delivered meets stability criteria. In an integrated power system, especially where there is an integration of renewable energy sources, the voltage profile and frequency often show fluctuations due to variation in source parameters. DC-DC converters are usually used in this situation to obtain a stable voltage level, frequency, and mitigate the harmonics and electromagnetic interferences (EMI) by implementing the filtering technique, and the major function is to convert the voltage level from one step to another step for appropriate use in the output.

The working of a DC-DC converter involves several stages and especially it plays an important role when the voltage level, frequency, and harmonic signal in the output are high. An unstable or uncontrolled direct current (DC) input is converted into a steady and dependable output voltage by DC-DC converters, which are essential power conversion equipment. The semiconductor devices (switches) such as MOSFETs, GaN HEMT, and SiC transistors are controlled through a pulse-width modulation technique to toggle the switching states. This switching process generates a pulsed waveform, which is then coupled to an isolation stage. To guarantee that the final power supplied to a load meets strict performance and stability requirements, these converters usually comprise multiple stages, such as rectification, switching, isolation, and filtering. Variations in the environment can cause significant fluctuations in input voltage and frequency in contemporary power systems, especially those that interface with renewable energy sources.

The power generation from renewable sources has ongoing fluctuations in power generation, causing turbulence in output voltage and frequency. The DC-DC converter is also used widely in other applications like DC motor driver systems, communication systems, and medical electronics. Moreover, the expected features of a DC-DC converter include an easy-to-control mechanism, the capability to reduce electromagnetic interference (EMI) noise, and decreased switching losses [17]. In general, DC-DC converters are of two types, isolated and non-isolated. An isolated converter generally uses a high-frequency transformer or sometimes opto-couplers to isolate the source and the load. In our application, an isolated DC-DC converter of step-down nature is used to obtain a filtered output voltage of 12 volts, and isolation is provided by high frequency transformer of 110 KHz. The design of the converter incorporates built-in protection features, including overcurrent, overvoltage, and thermal shutdown circuits to protect the converter and its connected loads, and it places a strong emphasis on a simple control mechanism to enable dynamic adjustment to quickly changing input circumstances. The reduction of EMI and the minimization of switching losses are also carefully considered; these are accomplished by using advanced semiconductor technologies, appropriate decoupling, and an optimized circuit layout. These factors are important not only for renewable energy and electric vehicle charging applications but also for other domains where power stability is essential, like medical electronics, communication devices, and DC motor driver systems.

The advanced and popular topologies that are commonly used in charging converters, renewable energy systems, and other power electronic circuits are discussed as follows;

2.7.1 LLC Resonant Converter

The DC-DC LLC Resonant converter employs two inductors and a capacitor to form a resonant circuit. This design enables the converter to switch power efficiently by minimizing energy loss during switching, a process known as zero-voltage and zero-current switching. They are mostly used in applications like electric vehicle charger converters due to their high efficiency and ability to handle varying loads.

2.7.2 LCL Resonant Converter

This topology also incorporates two inductors and a capacitor, forming a complex configuration of the resonant circuit. This is mainly useful to allow efficient power management in bidirectional power flow (Grid-to-vehicle and vehicle-to-grid). It is suitable for renewable energy systems and energy storage.

2.7.3 CLLC Resonant Converter

This topology involves the addition of one more capacitor in the LLC resonant circuit, which forms a more complex form of converter. This topology offers enhanced control over converters' operation, allowing them to efficiently manage bidirectional power flow.

Here are discussions of the other related research works;

Mortazavizadeh et al. (2021) discussed in their paper that GaN high electron mobility transistor (HEMT) significantly outperforms traditional silicon MOSFETs in terms of switching frequency, power density, and efficiency, enabling compact designs and reducing losses in applications such as adapters, electric vehicle chargers, and renewable energy systems. The study emphasizes that GaN-based LLC converters achieve zero-voltage switching (ZVS) with reduced dead time and lower gate driver losses due to minimized parasitic capacitances, making them suitable for high-frequency (MHz-range) operation. However, challenges such as electromagnetic interference (EMI), fringing losses, and reliability concerns under extreme conditions do persist, and there is a lot of scope in GaN HEMT to be explored further. The research also discusses interleaved topologies and integrated magnetics as solutions to improve current sharing and reduce magnetic component sizes, though these approaches introduce complexity in design and manufacturing. Furthermore, the authors compare GaN HEMTs with SiC and Si MOSFETs, demonstrating superior performance criteria like reduced total power dissipation and higher efficiency across varying frequencies. Despite their advantages, GaN devices face limitations in digital control system design, PCB winding optimization for high frequencies, and thermal management, necessitating further research into failure mechanisms and long-term reliability[18].

Liu et al. (2019) proposed a novel GaN-based LLC converter design integrating adjustable leakage inductance and optimized magnetics to address challenges such as component stress, proximity-effect losses, and thermal management in high-power-density applications. By utilizing a full-bridge topology on both primary and secondary sides, the study minimized voltage stress on switches while leveraging GaN’s ultrafast switching capabilities to achieve 97.03% peak efficiency at 500 kHz and 1 kW output power. The authors compared GaN HEMTs with silicon (Si) and silicon carbide (SiC) devices, demonstrating GaN’s superiority in minimizing switching losses and enabling compact designs. However, challenges such as electromagnetic interference (EMI) at high frequencies, core material limitations, and the need for advanced thermal management were noted. Future research directions include enhancing reliability under extreme conditions and scaling the design to higher power levels [19].

Huai Wei and Batarseh et. al. (1998) evaluated boost, buck, buck–boost, Cuk, and SEPIC converters in discontinuous conduction mode by analysing the input current waveforms and plotting voltage and current characteristic curves to assess each topology’s power-factor correction without an open-loop system. They have recommended extending the study to continuous conduction mode and developing adaptive control topologies to maintain high power factor under varying conditions[16].

Muhammad Faizan et al. (2023) presented a comparative analysis of a half-bridge LLC resonant converter using GaN HEMTs versus Si MOSFETs for low-power applications. The study employs simulation-based methodology to evaluate efficiency, power factor correction (PFC), and total losses. By utilizing GaN's lower output capacitance, gate charge, and switching time, the proposed converter achieves 98.5% efficiency with a 0.99 PFC, significantly outperforming the 87.4% efficiency and 0.92 PFC of Si MOSFET-based designs. The optimized magnetics and soft-switching properties further reduce conduction and switching losses by 37%, ensuring higher reliability and compactness. The findings conclude that GaN-based LLC resonant converters offer superior efficiency, reduced losses, and enhanced thermal performance, making them ideal for high-power-density applications, including potential scalability for EV charging systems [20].

Allan Taylor et al. (2018) conducted a comparative study on SiC MOSFET and GaN HEMT devices for a 7.2 kW EV battery charger. Their research highlighted that while GaN devices provided superior efficiency and reduced size, Silicon Carbide (SiC) devices demonstrated better thermal management under similar operating conditions. The study emphasized the potential of both technologies in EV charging applications but identified a need for a deeper understanding of their thermal performance across varying operational scenarios[8].

Hossein Rezaei and Abolfazl Babaei (2017) investigated the thermal behaviour of DC-DC converters incorporating high-frequency transformers. They found that transformer thermal performance significantly impacts overall converter reliability. Their research introduced improved methods for estimating power losses in transformers and highlighted the need for integrated thermal design. However, the study primarily focused on transformer losses, leaving gaps in the comparative thermal analysis of WBG semiconductors like GaN and SiC [21].

Satyaki Mukherjee et al. (2023) presented a high-power-density DC-DC converter using GaN transistors for universal EV charging. The converter achieved a peak efficiency of 98.2% with a wide output voltage range. Their findings demonstrated the feasibility of GaN for high-density applications but raised questions about its thermal limitations in prolonged operations. The study highlighted the need for further research on thermal optimization in GaN-based designs [15].

An analysis by Zhang et al. (2020) has explored the integration of SiC devices in high-voltage applications. They concluded that SiC devices excel in handling higher voltages and temperatures, making them ideal for robust applications. However, the study lacked a direct comparison with GaN, leaving a gap in understanding their relative performance in medium-voltage operation [22].

ElMenshawy and Massoud et al. (2019) explored the use of multimodule DC-DC converters for high-voltage, high-power renewable energy systems. They suggested arranging several converter modules in a row on the input side and side-by-side on the output side to handle large voltages and power levels more easily. This setup shares the workload across all modules, which boosts overall efficiency, improves reliability, and makes the system more resistant to failures and easier to expand. Their findings show that such multimodule converters offer a simple, flexible, and effective way to connect renewable energy sources to the power grid[17].

CHAPTER 3: METHODOLOGY

3.1. Background

There is a high demand for the development of descent, high-efficiency, high power density converters to meet the requirements of the modern world and for the proper and economic utilization of power utilities. Silicon-based DC-DC converters, though prevalent, encounter challenges like high switching losses, bulky components, and low power density, which limit their effectiveness in modern EVs. Gallium nitride (GaN), a wide-bandgap (WBG) semiconductor, offers superior material properties such as high electron mobility, low on-resistance (RDS (on)), and thermal resilience, enabling higher switching frequencies and reduced energy losses.

Considering the example of an EV charging application, DC-DC converters are essential for managing power flow between high-voltage batteries (e.g., 400V) and low-voltage systems (e.g., 12V), requiring compact and efficient designs. GaN-based LLC resonant converters could be excellent topology by achieving zero-voltage switching (ZVS) and operating at high frequencies (e.g., 110 kHz), shrinking passive components (e.g., transformers), and boosting power density and efficiency.

This research work holds simulation work in LTSpice to validate GaN-based designs, building on prior research demonstrating >95% efficiency in EV applications. Power factor correction (PFC) boost converters are also critical for grid compatibility, ensuring compliance with harmonic standards. By integrating GaN technology into a hybrid PFC-LLC system, this research aims to advance EV power electronics through simulation-driven loss calculation and efficiency analysis at resonating frequency.

3.2. System Architecture

The proposed GaN-based isolated DC-DC converter is designed and simulated in LTSpice software, and the design incorporates a noiseless critical boost Power Factor Correction unit, a Half-bridge Inverter circuit connected with an LLC resonant network, a high-frequency transformer, and a rectifier circuit as major components. The commonly available voltage level of 220 Volts is taken as input for the PFC converter, and it boosts the voltage level to 400 volts. This same voltage level is fed to the half-bridge inverter of the DC-DC Converter. The PFC converter topology. The switches used in the inverter a Gallium Nitride 650 volts, GS66516T. The GS66516T is an enhancement-mode GaN on-silicon power transistor. The properties of GaN allow for high current, high voltage breakdown, and high switching frequency. This is a top-side cooled transistor that offers very low junction-to-case thermal resistance for demanding high-power applications. These features combine to provide very high efficiency power switching.

Sequentially, the DC-DC converter has special design requirements of a half-bridge inverter, an LLC resonant network incorporating a high-frequency transformer isolating it with a rectifier circuit, and a battery or a load. A Half-bridge inverter is preferred in this application rather than other configurations as this configuration simplifies the network, and makes it cost-effective, efficient, and suitable in high-frequency and moderate-power scenarios. Half-bridge naturally supports ZVS operation in LLC converter, having lower switches is a cost-effective, and reduces the switching loss, and gate drive complexity is reduced by this phenomenon. The switches used in the inverter are Gallium Nitride (GaN) 650 volts, GS66516T. The GS66516T is an enhancement-mode GaN-on-silicon power transistor. The characteristics are presented in Table 2-1. The LLC resonant converter of DC-DC converter that operates based on the resonance of the inductor (L) and capacitor (C) components, typically consisting of a half-bridge or full-bridge inverter, a resonant tank (comprising resonant inductor (L), resonant capacitor (C), and magnetizing inductor (L_m), a transformer, and rectifier circuits on the secondary side.[18] One of the main advantages of using such a converter is its ability to obtain zero-voltage switching operation as well as zero-current switching in the secondary of the transformer, which reduces switching losses and enhances efficiency, especially at high frequency operation. Operating at around 110 kHz allows for maximum efficiency, and this allows for using smaller passive components (inductors and capacitors), resulting in a contribution to achieving higher power density and reduced weight and size of the converter. The transformer in an LLC resonant converter plays a crucial role, not only for voltage transformation but also as part of the resonant network, with the magnetizing inductance (L_m) of the transformer utilized as part of the resonant tank to help achieve soft switching. For a simple understanding of the system operation, a schematic layout diagram of the circuit simulation of the DC-DC LLC Resonant converter is illustrated in Figure 3.1.

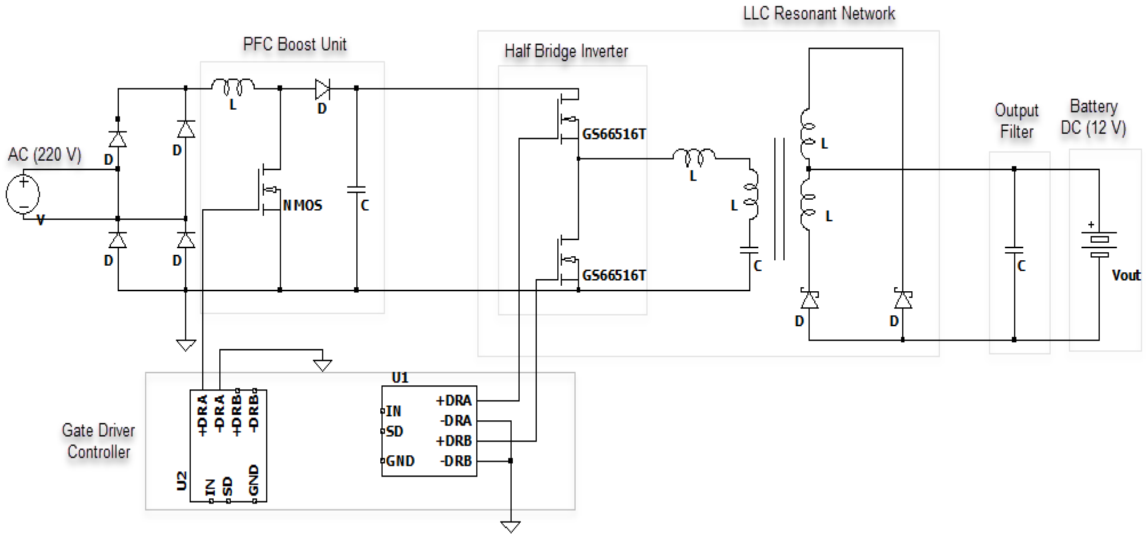

Figure 3.1: Schematic layout of the circuit diagram of the DC-DC LLC Resonant converter

3.2.1 PFC Converter Design

Power Factor Correction (PFC) Converter unit is a power supply module to the actual converter that rectifies the AC source in the household mains to a DC source using a full bridge rectifier circuit. The DC source is a non-regular output with ripple and harmonics in the waveform, where the PFC unit comes into play to fill the unstable DC output voltage and remove the harmonics and ripple effects using the filter circuit. Thus, after using a filter capacitor before the output terminal, a filtered 400 Volts DC output is obtained. A 220 Volts AC single-phase mains source is converted to DC voltage, and a boost circuit is implemented along with a capacitor as a filter circuit to mitigate the ripples, and an approximate range of 406 Volts is obtained as output from the circuit.

The simulation of the PFC Converter is completed in the LTSpice software. This includes four normal diodes forming an H-bridge rectifier circuit, the positive terminal of the rectifier is connected with the big inductor and a MOSFET as a switch in parallel. The switch gate voltage is given by the gate driver circuit. The capacitor is kept in as a filter circuit to give a proper ripple-less output voltage. The transient behaviour and steady state behaviour are analysed in the preceding context.

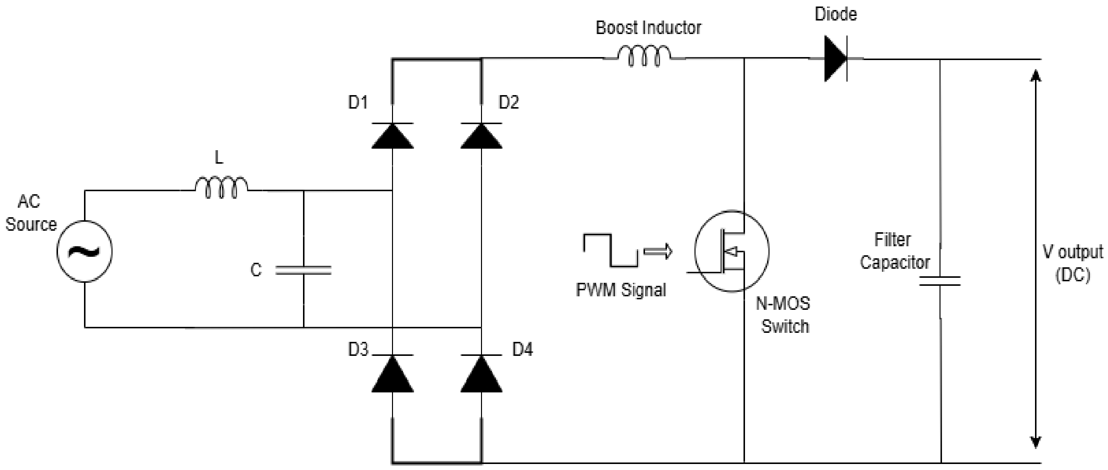

Figure 3.2: Schematic diagram of an isolated critical boost PFC controller

3.3. Half Bridge Inverter

The half-bridge inverter is a critical component in the GaN-based DC-DC converter system, particularly in the LLC resonant topology. This enables the efficient high-frequency operation for stepping down 400V to 12V in which can be utilized in suitable applications. the half-bridge inverter consists of two GaN HEMT switches (e.g., Infineon GT66516T) arranged in a bridge configuration with a midpoint connected to the resonant tank (Figure 3.1). It converts the DC input (400V) into a high-frequency AC waveform, which is then stepped down via a transformer and rectified to 12V. This uses only two switches (out of the normally four switches in a full bridge) to help reduce cost and complexity. The high-frequency operation of GaN minimizes passive component sizes, enhancing the power density of the device. The zero-voltage switching in a DC-DC Converter, or particularly in a bridge inverter, is achieved due to LLC resonant topology, eliminating turn-on losses and enhancing the efficiency of the converter.

The DC-DC LLC Resonant converter with a half-bridge inverter, a high-frequency transformer, and a rectifier with a Schottky diode. The isolated converter is illustrated in Figure 3.3.

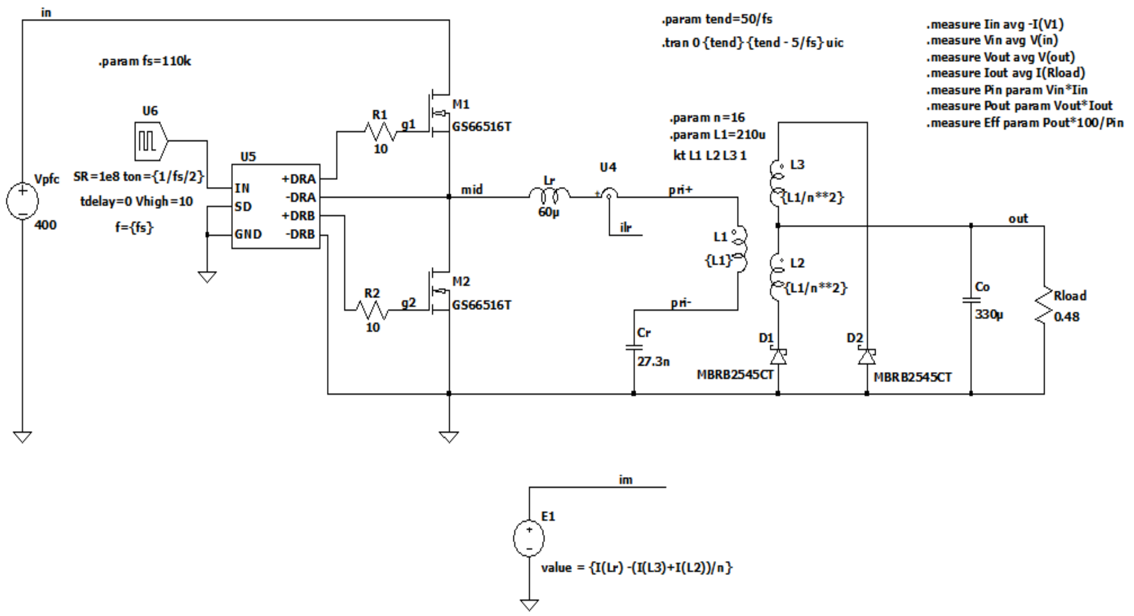

Figure 3.3: LTSpice simulation model of isolated DC-DC LLC Resonant Converter topology

3.3.1 Why Half Bridge?

The use of High-frequency operation reduces passive magnetic component sizes, helping with space and weight alignment for the EV charger. The use of a half-bridge inverter only consists of the two GaN switches, which obviously decreases the cost of comparatively expensive switches but also reduces the total voltage stress in the overall inverter circuit.

It helps in efficient to reduce the overall switching losses. The combination of a half-bridge inverter with LLC resonant helps to facilitate a zero-voltage switching process. The half bridge application enables the thermal efficiency of the overall converter, and it's easier for cooling even at very high efficiency.

3.4. Gate Driver Circuit Design

A gate driver circuit is essential to control the switching of GaN HEMTs in a half-bridge inverter, ensuring efficient operation in high-frequency LLC resonant converters. It supplies voltage/current to the GaN HEMT gate to switch it between on and off states. It manages dead time to prevent shoot-through in half half-bridge inverter, and also mitigates parasitic effects such as the ringing effect and overshoot effect caused by GaN ultra-fast switching speed. GaN's high switching speeds require careful layout to avoid false triggering.

3.5. LLC Resonant Network Operation

The circuit seen in Figure 3.4 is subdivided into the output rectifier circuit, the output filter, the transformer, the square-wave signal, and the series resonant tank. The square wave generator, which commutates at 50% duty cycle, is carried out by Q_{i1} and Q_{i2}. A series resonant inductor (L_r), a series resonant capacitor (C_r), and the Lm provided by the transformer's magnetizing inductance (HFT) comprise the series resonant tank. The leakage inductance of an HFT or an external component may act as a series resonant inductor. The resonant current is changed into a unidirectional current for the rectifier circuit, which includes the S_{r1} and S_{r2} Schottky diodes. The high-frequency ripple current is altered by the output filter (C_f).

In a traditional series resonant converter (SRC), which can only operate beyond the resonant frequency to achieve the ZVS condition and includes an infinite magnetizing inductor, L_m, the SRC DC gain is always less than 1 in this condition. However, in an LLC converter, the magnetizing inductor (L_m) is substituted with a shunt inductor that works the best conditions during the resonant frequency and also works above and below the resonant frequency. The following modes of operation take place in the LLC topology [13].

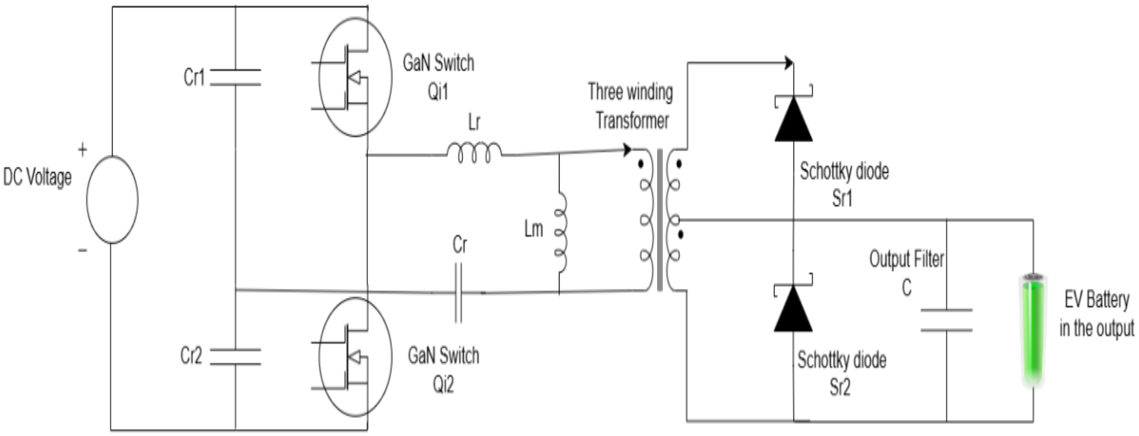

Figure 3.4: LLC Resonant DC-DC Converter topology

I. Operating Waveform at (f_s<f_r)

While the switching frequency is less than the resonant frequency, the resonant current discharges and then flows through the diode of Q_{i1}. The diode in the output supplies power to the load, and the magnetizing current gradually increases. When Q_{i1} gets under zero-voltage switching, the current first drops to zero, direction reverses, and flows through Q_{i1}. As f_s is low, the switch S_1 stays operated for longer, and the current gradually matches up until it matches the load requirement.

II. Operating Principle at (f_s=f_r)

The condition when switching frequency is equal to the resonant frequency, the shape of the resonant current resembles a sinusoidal behaviour. It works in the phenomenon of boundary conduction mode (BCM). This gives minimum conduction loss and maximum possible efficiency.

III. Operating Waveform at (f_s>f_r)

When the switching frequency is greater than the resonant frequency, the switches S_1 and diode D_1 turn on, and the resonant capacitor and resonant inductor start resonating. The magnetizing current gradually increases, but the switch Q_{i1} turns off before the resonant current catches up. The remaining current flows to the load from the body diode of the S_{r2} switch while the output voltage blocks the current and declines fast. When Q_{i2} turns on under zero-voltage switching, the current reduces, equalizing the magnetizing current, and diode D_1 turns off. Zero-voltage switching is maintained, but zero current switching is lost due to forced current shutdown.

3.6. ZVS Operation

Zero Voltage Switching is a soft-switching technique where a power semiconductor device is turned on or off when voltage across its terminals is zero or near zero. This eliminates switching losses during the fast switching operation, whereas there is a high switching loss during hard switching. ZVS minimizes switching losses by ensuring the device voltage drops to zero before turn-on. The LLC resonant tank comprises the resonant inductor, magnetizing inductor, and resonant capacitor; the magnetizing current acts as a current source during dead time to discharge parasitic capacitance. GaN devices used in the application enhance ZVS due to their low output capacitance. ZVS eliminates voltage current overlap during turn-on, which is critical for high-frequency operation. Lower losses are also applicable for compact designs of the device along with reduced cooling requirements.

3.7. High Frequency Transformer

The high frequency transformer is a voltage conversion static electrical device whose operating frequency is very high, and also a three-winding transformer is utilized in the topology. It converts high alternating voltage at high frequency into a lower alternating voltage, which is further rectified to supply to the output. The use of high-frequency transformers is small in size, and it also helps to reduce the size of the passive components in the circuits, like capacitors and inductors, associated with the filter circuits. The transformation ratio for the high-frequency transformer is given by equation 7 in section 3.10. Their operating capacity is up to a range of megahertz. So, they are utilized along with the wide band gap switches and applications where high switching frequency is required.

The use transformer integrates (Lr) and (Lm), enabling compact magnetics. In GaN-based designs, high-frequency operation reduces core size but increases winding losses due to skin and proximity effects. A key challenge is asymmetrical primary/secondary currents caused by current due to magnetizing inductance, inducing a phase shift that exacerbates eddy current losses.

3.8. Rectification Process

The rectification circuit includes a Schottky diode instead of a regular diode. Schottky diode helps to achieve superior properties as a semiconductor device; their forward voltage drop also has a fast switching speed with negligible recovery time. It enhances reduced switching losses and helps in increasing efficiency in rectification. Schottky diodes are also suitable for high thermal management and high-frequency operation. However, they have limitations, including lower reverse breakdown voltages (up to 200 Volts) and higher reverse leakage currents.

In the rectification process, a center-tapped transformer with two Schottky diodes creates a full-wave rectifier where each diode conducts on alternating half-cycles, and the output obtained is smoothed by a filter capacitor. The two-diode configuration reduces the component use and lowers the forward drop voltage by half in comparison to the full bridge, and also reduces losses and enhances efficiency. The low forward voltage and rapid recovery of Schottky diodes also minimize switching losses. This configuration mandates a center-tapped secondary winding and a carefully designed transformer to ensure balanced load sharing. The Schottky devices also have lower reverse voltage ratings and higher leakage currents, which might require a snubber circuit or additional filter circuits to control leakage and voltage stress.

3.9. Software Used

LTSpice (Linear Technology Spice) software by Analog Devices. LTSpice is used to simulate the critical boost PFC converter and LLC LLC-based DC-DC converter in this application. The availability of simulation models of GaN HEMT switches makes them suitable to be used in this software with ease, and those models are available on the company website, whereas they are not easily implementable in MATLAB/Simulink and other simulation software. LTSpice models feature a high degree of freedom in reconfiguring the properties of the components used, as well as analysing the computation by formulating a mathematical expression The LTSpice is a free power electronics simulation software that has an easy installation process, and is a high-performance simulation tool widely used in academic and industrial applications. The following are the advantages of using this tool;

- Cost-effective as it is free to use and provides a powerful simulation platform without licensing fees.
- Comprehensive component library, as it includes library of SPICE models and analog devices as well as simulation blocks can be uploaded with ease available at various online platforms.
- The interface is user-friendly, and the simulation speed is high.
- LTSpice is very useful to adjust and design the components as per the user's requirements.

There are also a lot of challenges associated with using this software. Though simpler circuit design is easier after a short work in the software but it is complex for complex circuit designs. It faces challenges in convergence issues in complex, non-linear circuits due to high-frequency operation, abrupt transition, floating nodes, or unsuitable component values, which lead to runtime errors. All third-party SPICE components are not fully supported by LTSpice; users might have to modify syntax of the syntax or adjust parameters.

3.10. Mathematical Formulation

Integrating a power factor correction unit and a DC-DC converter is a critical step in designing a system that efficiently converts 220 Volts AC to a filtered output of 12 Volts DC. This focuses on assembling two major systems to ensure high efficiency, compliance with harmonic standards, and stable operation under varying load conditions. A continuous conduction mode (CCM) boost converter topology is chosen for its ability to achieve a high-power factor (>0.99) and low total harmonic distortion.

The parameters of the PFC converter are presented below as;

- F_{max}= Maximum Switching Frequency
- F_{min} = Minimum Switching Frequency
- V_{pfc} = Output Voltage
- V_1= Source Voltage
- R_1= Load Resistance
- L_1= Converter Inductor
- $\hat{V}$= Ripple Voltage

The on-time period of the switches is given by the equation;

$$T_{0N} = \frac{1}{F_{\max}} \tag{1}$$

The output voltage of the PFC converter is given by;

$$V_{\mathrm{Pfc}} = V_1 \cdot \sqrt{R_1} \cdot \frac{4 \cdot L_1}{T_{0N}} \tag{2}$$

The minimum possible operating frequency can be calculated using this equation;

$$F_{\min} = \frac{1}{T_{0N}}\left(1 - \frac{V_1}{V_0}\right) \tag{3}$$

There is a ripple voltage remaining as AC components and harmonics persist in the output ripple quantity. 1% of the output voltage is considered the ripple voltage.

$$\hat{V}_0 = 1\% \text{ of } V_0 \tag{4}$$

The filter capacitance is given by;

$$C = \frac{P_1}{4\pi \cdot V_0 \cdot \hat{V}_0 \cdot f_s} \tag{5}$$

The zero-voltage switching charge balance equation for the primary side half-bridge topology is given by;

$$I_{L_{m-\mathrm{pk}}} T_d = 2C_{\mathrm{pri\_oss}} V_{\mathrm{in}} + C_w V_{\mathrm{in}} + \frac{1}{N} \cdot 2nC_{\mathrm{sec\_oss}} \cdot 2V_o \tag{6}$$

Where,

- $I_{L_{m-pk}}$ = peak magnetizing current,
- T_d = Dead time,
- $C_{\mathrm{pri\_oss}}$ = Primary-side device output capacitance,

- $C_{\text{sec\_oss}}$ = Secondary-side device output capacitance,
- C_w = Transformer winding capacitance (referred to primary),
- n = Number of secondary-side parallel devices,
- N =transformation ratio
- V_{in} = Input voltage,
- V_o = Output voltage

The turns ratio of the high frequency transformer is given by;

$$N = \frac{V_{\text{in}}/2}{V_o} \tag{7}$$

Considering the current waveform from (t_0 to t_1), in Figure 3.4, the magnetizing current is given by;

$$I_{L_{m-pk}} = \frac{NV_o\left(\frac{T_t}{2} - T_d\right)}{2L_m} \tag{8}$$

When combining (1), (2), and (3), the value of magnetizing inductance becomes;

$$L_m = \frac{T_d\left(\frac{T_s}{2} - T_d\right)}{4\left(2C_{\text{pri\_oss}} + \frac{1}{N^2}\cdot 2nC_{\text{sec\_oss}} + C_w\right)} \tag{9}$$

The secondary side current I_{s1} or I_{s2} equals the current in primary side I_p minus I_{L_m}[7]. And the average secondary current after rectification can be computed as;

$$N \cdot \frac{2}{T_s}\int_0^{\frac{T_L}{2}-T_d} \left(I_p - I_{L_m}\right)dt = \frac{V_o}{R_L} \tag{10}$$

The RMS current in primary-side is given by;

$$I_{\text{rms'}}^{-\text{P}} = \sqrt{\frac{V_o^2 T_s^2 \pi^2}{8R_L^2 N^2 (T_s - 2T_d)^2} + \frac{1}{2} I_{L_{m-\text{pk}}}^2} \tag{11}$$

Including the magnetizing current during the dead time, the total RMS current is given by;

$$I_{\text{rms\_P\_total}} = \sqrt{\frac{V_o^2 T_s^2 \pi^2}{8R_L^2 N^2 (T_s - 2T_d)^2} + \left(\frac{1}{2} + \frac{2T_d}{T_s}\right) I_{L_{m-\text{pk}}}^2} \tag{12}$$

The secondary-side RMS current is given by;

$$I_{\text{RMS\_S\_total}} = N\sqrt{\frac{T_s - 2T_d}{2T_s}\left[I_{\text{RMS\_P}}^2 + \left(\frac{1}{3} - \frac{8}{\pi^2}\right) I_{L_{m-\text{pp}}}^2\right]} \tag{13}$$

From equations (12) and (13), it can be seen that the dead time and peak magnetizing current impact the RMS current in the primary and secondary of the transformer. Large dead times or peak currents increase conduction losses and result in inefficient energy transfer. Therefore, small peak magnetizing current, small dead time, and the overall device capacitance that takes part during the dead times ought to be minimized[15].

Thus, utilizing the following design topologies and use of Gallium Nitride-based switches in the converter, enhances the efficiency and reduce losses than the conventional design methodology and utilization of silicon-based switches.

CHAPTER 4: RESULTS AND DISCUSSION

The design of a Gallium Nitride-based LLC resonant DC-DC converter topology incorporates the noiseless critical boost PFC converter unit, half-bridge inverter, and the high-frequency transformer, along with a rectification unit. The PFC unit converts a 220 Volts AC electrical signal into a 406 Volts DC filtered output. The output voltage is further fed to the half-bridge inverter, which is implemented to reduce the complexity of the circuit and considering the advantage of facilitating zero-voltage switching and reducing voltage stress on the switches. The inverter converts a DC 406-volt supply into high frequency square wave signal. The signal is fed to the high-frequency transformer via an LLC resonant network. The LLC resonant network functions to operate the circuit functionality with varying frequency limits and gives the output based on that. The circuit gives the minimum impedance while the switching frequency of the switches in the inverter, which is controlled by the gate driver circuit, equals the resonating frequency of the LLC resonant network; otherwise circuit operates with higher losses and lower efficiency. The LLC resonant network is connected to the primary of the high-frequency transformer. The use of high high-frequency transformer in an LLC Resonant DC-DC converter is to convert the voltage level either step down or step up. In this application, the transformer works as a step-down transformer that is required for matching load requirements and converts the output voltage to around 13 volts. High-frequency transformer also provides galvanic isolation, which is essential for safety in the isolated converters. This also helps to enable high power density as it operates in very high frequency operation, helps in zero voltage switching in integral with LLC topology. GaN-based LLC resonant DC-DC converter consists of a rectifier circuit on the secondary side of the transformer that uses Schottky diodes to convert a high-frequency AC signal into DC. Schottky diodes are used in rectifier circuits because they have a low forward voltage drop, which reduces conduction losses and improves efficiency. Their fast switching capability also makes them suitable for high-frequency operation, ensuring reliable and efficient rectification.

The simulation of the research is completed in LTSpice software, as wide band gap switches are easy to implement in it, rather than in software like MATLAB/Simulink. From the simulation of the overall converter topology, the following observation can be made in the PFC circuit, followed by the DC-DC converter. The circuits are designed and simulated in LTSpice software and are represented below. From an AC mains source of 220 Volts, to output DC voltage of 13.148 Volts is obtained.

4.1. Power Factor Correction Unit Output

The Figure 4.1 represents the input AC sinusoidal voltage source of 220 Volts supplied to the PFC converter and obtained a stable filtered output of 406 Volts DC output as PFC circuit boosts the voltage level to high level as per the demand and this is controlled by the value of inductance of the inductor and switching frequency of the semiconductor switch.

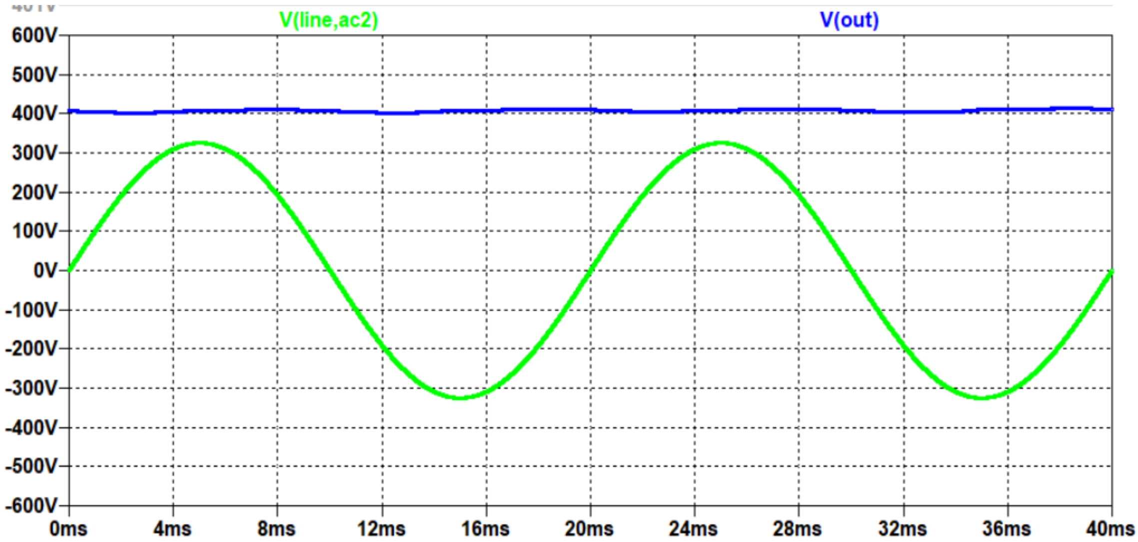

Figure 4.1: Input voltage and Output voltage waveform of the PFC converter unit

The Gate, Source, and Drain current and voltage waveform of the MOSFET switch implemented in the PFC converter are analysed and represented in Figure 4.2. V(gate) represented by the blue line, showing an approximate voltage level of 15 Volts, V(n003) represents the source to drain voltage of 406 Volts DC. It is seen that it is only triggered during the low-voltage profile of the Gate voltage. Ig, Id, and Is represent the current through the gate, drain, and source.

Furthermore, the obtained 406 Volts of DC output from the PFC Converter is supplied to the half-bridge converter of the DC-DC converter. The half-bridge converter is preferred in this design for cost, feasibility, compact design, and mainly due to its accessibility of zero voltage switching operation phenomenon in coordination with the LLC Resonant network. The Gallium Nitride switches of Infineon Company, GS66516T GaN switch of 650 operating voltage, very low on-state resistance, and high thermal characteristics of 25 °C to 150 °C. The properties of GaN switch GS66516T are shown in Table 2-1.

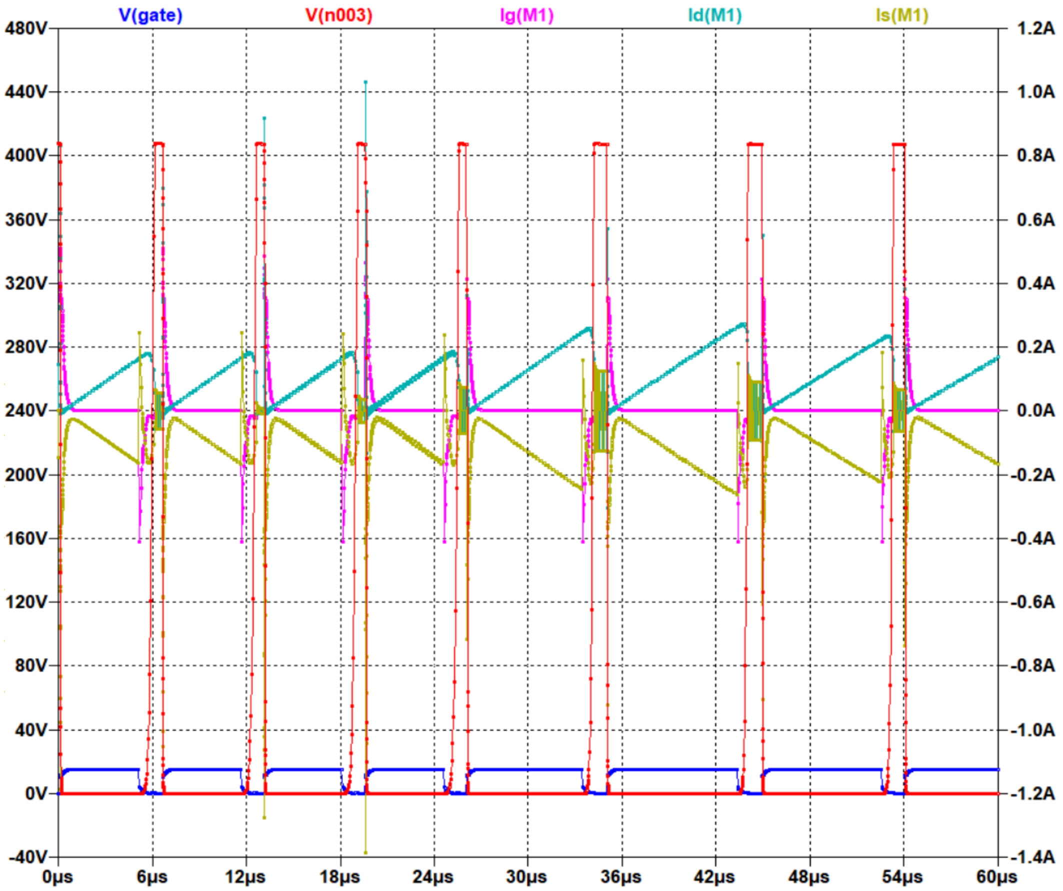

Figure 4.2: Gate, source, and Drain Current and Voltage waveforms for PFC Converter switches

The parameters and outputs associated with the critical boost power factor correction unit are presented in Table 4-1.

Table 4-1: Power Factor Correction unit parameters

Parameter	**Value**
Source Voltage	220 Volts
Source Frequency	50 Hertz
Inductor	1.32 mH
Switching Frequency (max)	200 kHz
Switching Frequency (max)	37.4 kHz
Switch On time (Ton)	.05 mSec
Output Voltage	406 Volts

4.2. DC-DC Converter Output

The DC-DC converter section includes half half-bridge inverter, which consists of two wide-band gap GaN switches (GS66516T model GaN switch from Infenion), LLC resonant network with magnetizing inductor, resonant inductor and resonant capacitor, a high frequency transformer to convert high voltage signal to lower voltage signal and provide isolation between the load and the converter and it is followed by rectifier circuit along with output filter capacitor to obtain filtered DC output voltage. The load is represented by a resistive load in the simulation, and the results are computed.

The current and voltage waveform of the GS66516T GaN switches is represented in Figure 4.3. I(R1) and I(R2) represent the current through the source to drain of the first and second switches, and V(g1) and V(g2) represent the gate voltage across the first and second switches, respectively.

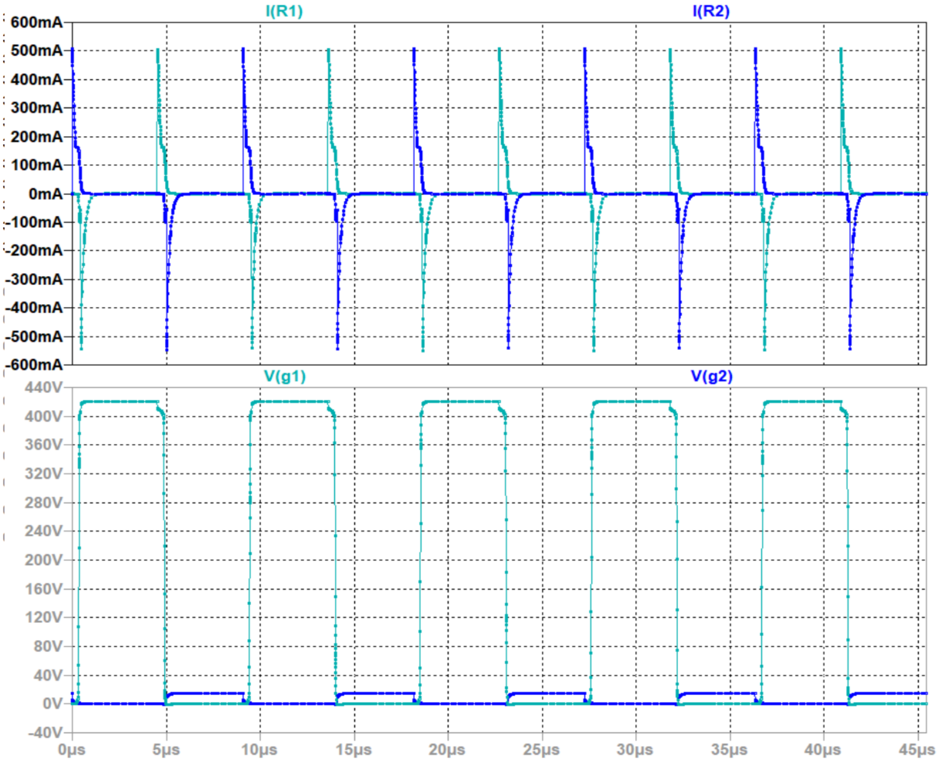

Figure 4.3: GS66516T GaN switch current and voltage waveform for DC-DC Converter

Further, there is a great role of the LLC resonant network in the circuit to achieve zero voltage switching of the switches, which helps reduce the switching and conduction losses and enhances the converter's efficiency. The primary and secondary voltage and current levels are represented in Figure 4.4.

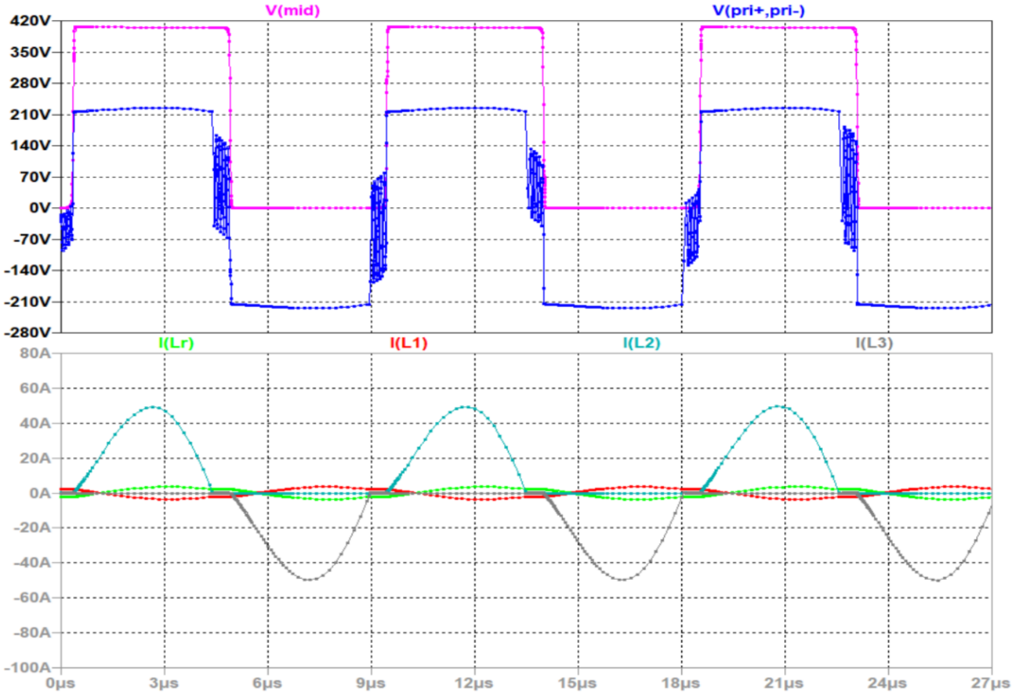

Figure 4.4: Primary and Secondary current and voltage of the transformer in the DC-DC converter

The comparison of the outputs of the Gallium Nitride converter and the silicon converter at the frequency of 110 kHz is tabulated in Table 4-2. The data in the table shows that at the switching frequency of 110 kHz, GaN (Gallium Nitride) switches exhibit superior performance compared to traditional Silicon switches. Specifically, GaN achieves an efficiency of 95.887%, which is a 1.288% improvement over the Silicon converter's 94.59%. Also, GaN switches have significantly lower switching losses (0.74397 W) compared to Silicon's 1.72126 W. These enhancements are attributed to GaN's faster switching speeds and reduced conduction losses, enabling higher power density and efficiency. However, adopting GaN technology involves trade-offs, including higher costs and increased design complexity, particularly in thermal management and circuit layout. Having these challenges, the efficiency enhancement and potential for more high-power density and compact converters, high-performance converters make GaN a compelling choice for advanced power conversion applications.

Table 4-2: Outcomes representing Silicon and Gallium Nitride converter at 110 kHz

Parameters	Silicon Switches	Gallium Nitride Switches
Input Current	0.72759 A	0.94481 A
Output Current	26.60791 A	27.39166 A
Output Voltage	10.49650 V	13.148 V
Input Power	295.4023 W	383.5930 W
Output Power	279.2971 W	367.8170 W
Efficiency	94.59972%	95.88728%
Switching Loss	1.72126 W	0.74397 W

4.2.1 Switching loss reduction

Figure 4.5 represents a snapshot of the simulation result based on the Silicon converter, and it shows the drain current, source to drain voltage, and the product of them signifies the losses that occurred in the switches. The mathematical expression is formulated for the losses in the LTSpice software. Each time simulating the circuit using a GaN switch and a Si switch, the losses are computed and are recorded for analysis purposes.

The data are tabulated in the appendix Tables A and B, they are also represented in a line graph. Such a comparison helps to analyse what percentage loss used to be on the silicon-based converter, as when losses are higher, the efficiency of the converter is lower, and it consumes the electricity input for the higher rating but works lower than that. Thus, in the case of updated and lower switching loss GaN switch implementation will help the proper utilization of electrical energy. In a long-term vision of utility development, using highly efficient converters always helps the development of lower rating power plants and lower ampacity conductor lines in the transmission line, as it can fulfill the required power demand.

The switching losses are moreover important while analysing the efficiency of the converter, and the abrupt change in switching loss appears while comparing the results of the silicon-based and gallium nitride-based converter. At the switching frequency of 110 kHz, the GaN switch exhibits lower switching losses of 0.74397 Watts compared to Silicon losses of 1.72126 Watts, with a remarkable 56.8% reduction. Also, while considering the switching losses at all the frequencies, the overall reduction in switching losses is by 59.2 %. Such reduction is attributed to GaN's faster switching speeds and lower output capacitance, which minimize energy losses during transitions. Consequently, GaN devices enhance efficiency and support switching frequencies, leading to compact and efficient power conversion systems. Despite higher costs of GaN switches and design complexities, the performance benefits make GaN a compelling choice for advanced power applications.

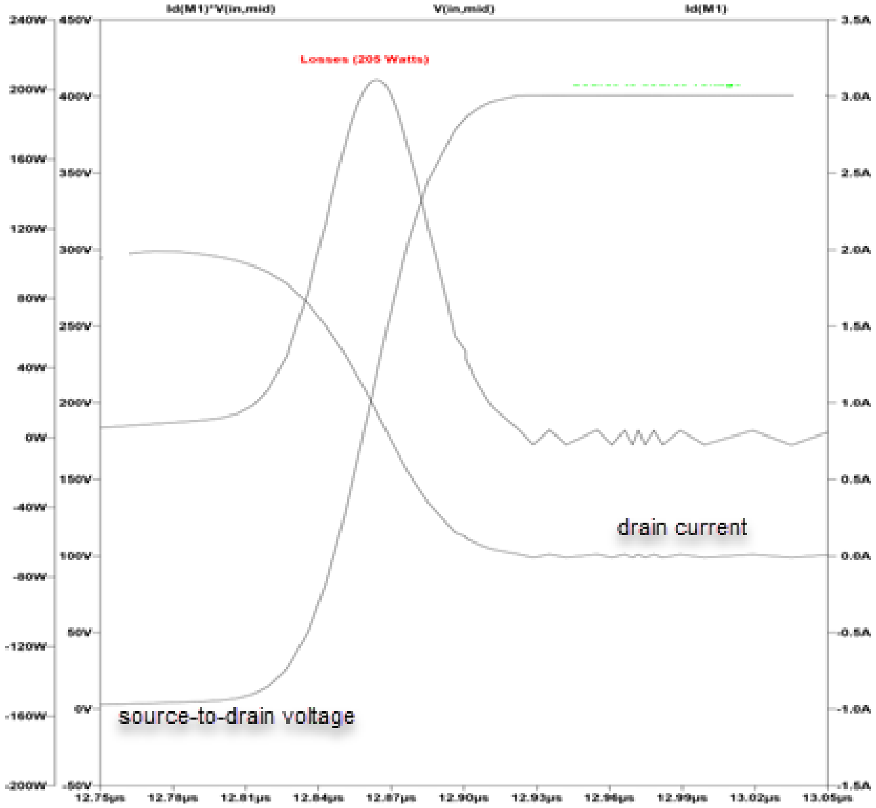

Figure 4.5: Switching loss in a Silicon switch-based converter

The final output of the DC-DC converter topology is illustrated in Figure 4.6, which shows the conversion from 406 Volts of DC supply to 13.148-volt filtered DC outputs. As we know, the current flows from the higher potential point to the lower potential point, so this obtained filtered DC voltage is used to charge a 12-volt range of battery in a constant voltage mode of charging. The output current can vary as per the loads connected. In Figure 4.6, we can see the straight-line representation of 406 volts, which is a filtered, ripple-less output voltage from the power factor correction unit, and alternating voltage in the upper half signifies that the output voltage is stable with the accuracy of 0.10 volts as it ranges from 13.10 Volts to 13.20. So, this output is suitable for supplying to the loads.

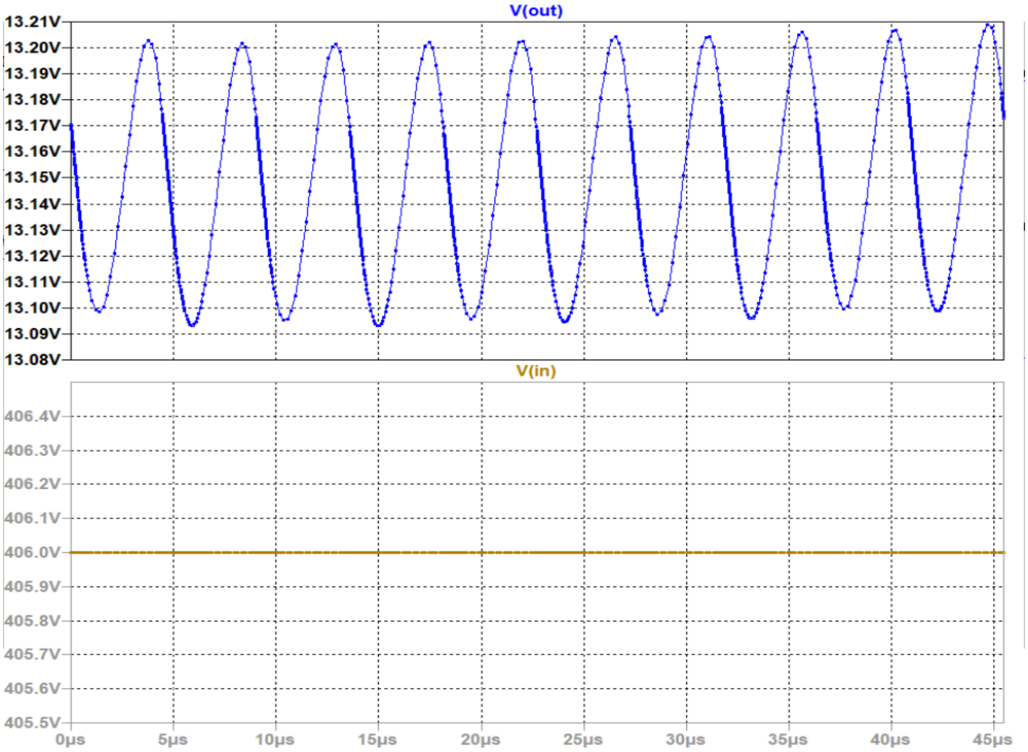

Figure 4.6: Input and Output voltage waveform of DC-DC Converter

The resonance frequency is obtained while the operating frequency across the switches in the half-bridge inverter is varied from 50 kHz to 200 kHz, and the maximum efficiency is plotted at 110 kHz resonant frequency. The parameters and the ratings of the DC-DC converter are as illustrated in Table 4-3.

Table 4-3: LLC Resonant DC-DC Resonant converter parameter

Parameter	**Value**
Power rating	330 W
Input voltage	406 Volts DC
Output voltage	13.148 Volts DC
Switching frequency(resonant)	110 kHz

While computing the power output, the voltage and current waveforms, and efficiency of the converter using Gallium Nitride, a formulation is set up in the LTSpice simulation model to analyse the results. The results are computed by varying the switching frequency of the switches, and at the resonant frequency, the obtained efficiency of the converter is found to be maximum. The converter's efficiency is maximum at the resonating condition, as the impedance is the lowest. Switching losses are minimum, as it enables ZVS and ZCS, and the switching operation is smoother. So, maximum power transfer is possible, and energy is better recycled between the inductor and capacitor. Thus, upon simulating the circuit using Gallium Nitride and operating it in various frequency ranges, the maximum efficiency was obtained at 110 kHz. Thus, this is considered the resonant frequency. Our objective of this research was also to compute the efficiency and losses associated with Gallium Nitride, and also compare the results with those obtained using Silicon as a switching device.

Thus, initially, the power output, voltage, efficiency, and losses for the Converter with GaN were computed and tabulated, and similarly computed for the converter with a Silicon switch. They are compared and presented in the line graphs. The comparison of output power versus frequency is plotted in Figure 4.7. This signifies that the output higher output power transfer is possible by the use of GaN, as switched at every switching frequency.

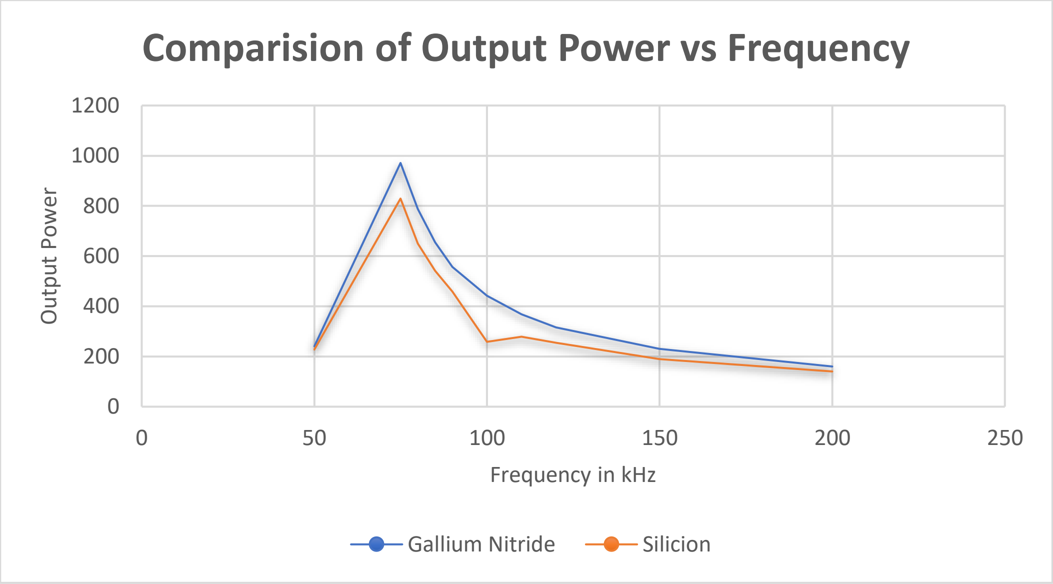

Figure 4.7: Comparison of output power versus frequency among Si and GaN

The comparative graph of output power versus the varying efficiency is illustrated in Figure 4.8. The results depict that a maximum power transfer always occurs in the case of Gallium Nitride switches, and the simulation result it shows maximum power at 75 kHz of frequency.

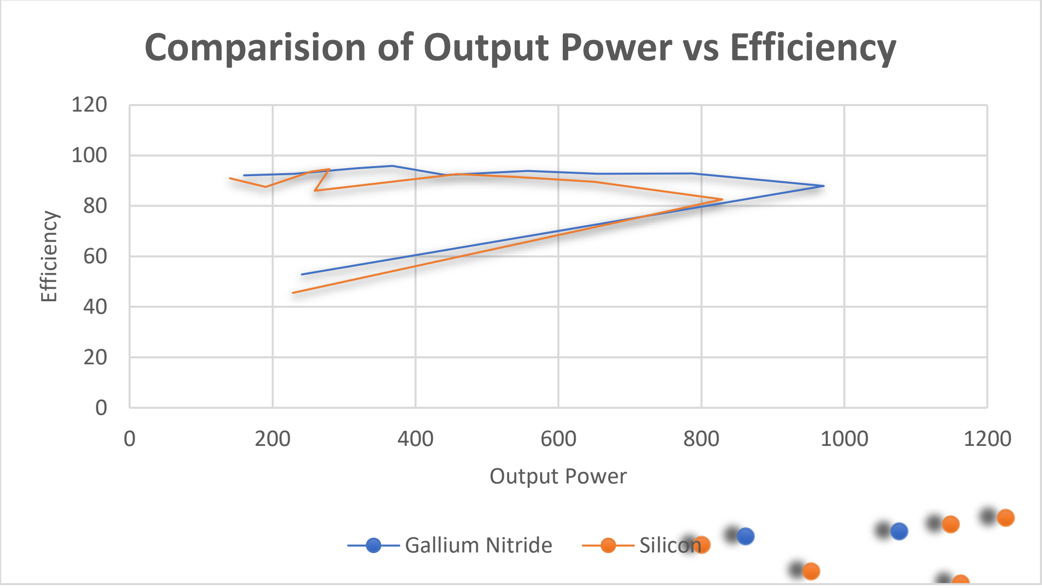

Figure 4.8: Comparison of output power versus efficiency among Si and GaN

Figure 4.9 represents the comparison of switching losses among Silicon and Gallium Nitride switch operation. The graphs show that the losses for GaN are comparatively lower in range than at any instant. This signifies that switching loss is remarkably reduced while utilizing GaN.

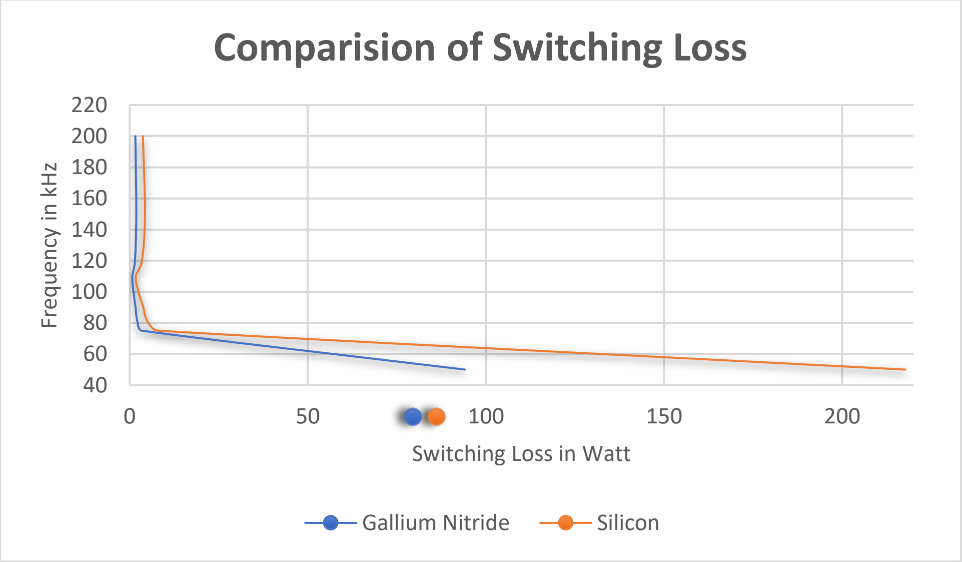

Figure 4.9: Comparison of switching loss among Si and GaN

The most important thing that makes a significant difference and consideration is the comparison of efficiency between the Silicon and Gallium Nitride switches. As efficiency includes the overall computation of current, voltage, and losses, the efficiency of the converter with GaN at a resonating frequency of 110 kHz was found to be 95.887 %. The efficiency of the converter at the same resonating frequency with Silicon switches was found to be 94.59 %. The reduction of switching loss in GaN HEMT switches from Silicon switches converter is by 56.8 %. This shows a good improvement in the case of switching loss, which also enhances the efficiency while using the GaN switches by 1.288%. The graph in Figure 4.10 illustrates the comparison of efficiency with varying frequency among Silicon and Gallium Nitride.

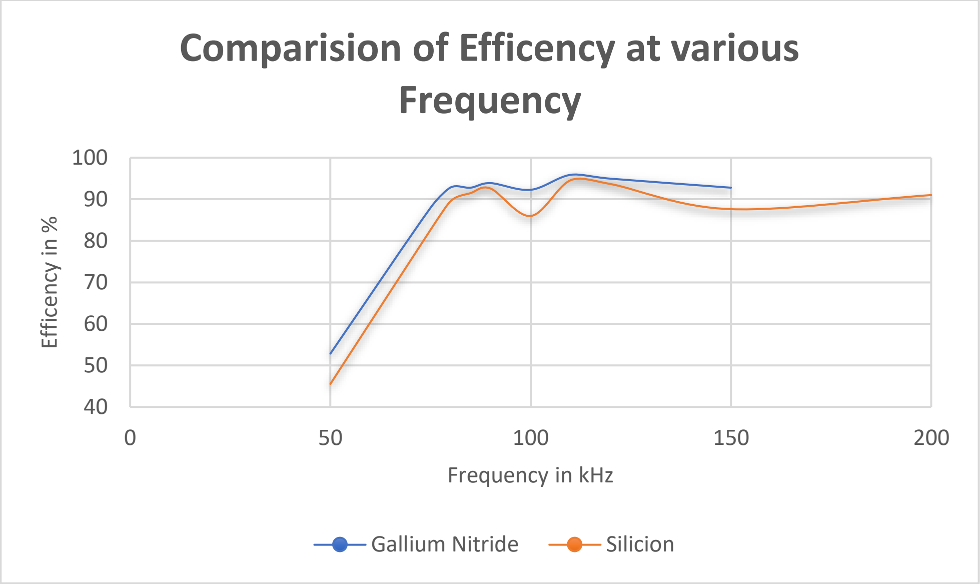

Figure 4.10: Comparison of Efficiency and varying frequency among Si and GaN switches

4.3. Comparative analysis of GaN and Si-based converter outcomes

The simulation was performed for Silicon-based converter and Gallium Nitride-based converter for a varying range of frequencies ranging from 50kHz to 200kHz, and the output current and voltage, output and input power are computed using the mathematical representation in the LTSpice software itself, along with switching losses and frequency. They are recorded, and the data are plotted in a graphical representation to analyse the outcomes.

From the comparative analysis of output power versus Frequency, it is evident that the power transfer capability while utilizing a silicon switch is lower at every switching frequency than using a GaN switch. Comparing the switching losses, there is a drastic reduction of switching losses in the case of the GaN-based converter than in Silicon-based converter. This outcome is advantageous from every point of view because it enhances efficiency, facilitates the use of higher switching frequencies, which helps in the reduction of the size of passive components, capacitors, and inductors, which reduces the size of the converter and increases the power density. The reduction of passive components in the connected loads is also a better result for the power supply utility, as reactance reduces in the system. Also, from the comparison of the efficiency graph, an increase of efficiency by 1.288% was recorded, which signifies the importance of using GaN-based switches in the converter applications. Though there are numerous advantages of using GaN switches, they also have several shortcomings, like their higher device cost and robust and descent PCB design layout, and thermal management challenges. GaN switches utilize advanced packaging techniques like Ball Grid Array (BGA) methods to enhance performance, minimize unwanted parasitic inductance, and improve heat dissipation. Whereas, silicon-based switches are packaged traditionally, which is bulkier but easier to implement and accommodate circuit layouts.

Overseeing the results obtained for the LLC Resonant DC-DC converter utilizing Gallium Nitride and also comparing the output with Silicon switch converter, we obtained the maximum efficiency of the converter of 95.887 % while using GaN switches at the resonating frequency of 110 kHz, while for the same frequency and similar conditions, the Si switches obtained an efficiency of 94.59%, which shows a rise in efficiency at high operating frequency. The filtered DC output voltage of 13.148 Volts is obtained. The switching losses are significantly reduced, which is possible due to the low on-state resistance of the GaN switches and zero voltage switching. Despite these technical advantages of the GaN switches in the converter, they aren’t commonly available and are expensive in comparison to Silicon-based switches. But due to the improvement of power quality index, reduction of total harmonic distortion and switching losses, and remarkable improvement of efficiency.

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATIONS

The design and simulation of an LLC resonant DC-DC converter based on gallium nitride (GaN) and comparing the results with a silicon-based converter, and achieve higher efficiency and reduce switching and overall conduction losses, was the main objective of this research. The converter achieved a peak efficiency of 95.89% at an output power of 360.15 W and an output voltage of 13.14 V. Additionally, 110 kHz was the switching frequency at which this best performance was attained which is considered the resonant frequency of the converter using Gallium Nitride power semiconductor as the switches. The GaN-based design achieved a significant reduction in losses and an efficiency improvement of 1.288% in comparison to conventional silicon-based converters. Also, the switching loss is found to be reduced by a significant 56.8% from the Silicon-based converter to the GaN HEMT switch converter. These results highlight GaN's excellent material attributes, particularly its lower on-resistance and better electron mobility, which allow power conversion devices to operate more efficiently and with less heat dissipation. This helps design smaller heat sink devices, and the size of the converter for the same power rating is reduced, increasing the power density of the device.

The implications of this research suggest that the design methodology of the DC-DC Converter is implementable for use in several applications, including the Electric Vehicle Charging station and various renewable energy conversion purposes, which could be advantageous, as a significant enhancement in efficiency is noticed in the Gallium Nitride-based converter in comparison to the Silicon-based converter. The losses are significantly reduced with a half-bridge inverter, and an LLC resonant converter topology facilitates zero voltage switching, which results in lowering the switching losses and also a reduction in total harmonic distortion. The power transfer capability is also higher for the GaN-based converter. Technically this suggests that the implementation of Gallium Nitride-based converters is better to be implemented in the renewable energy harvesting purpose as well as in charging electric vehicle application. Power production and distribution utility and consumers benefit economically as the converters are highly efficient, i.e., they have to pay a tariff for lesser losses. The utility has the maximum benefit from such kinds of converter implementation, as the impact of the charging station causes high total harmonic distortion due to the connection of a non-linear load system and injects reactive power into the system but using this converter the THD are significantly reduced and the size of the passive components like inductors and capacitors are minimized. In contrary, the availability of the Gallium Nitride is limited as for now and it is expensive to implement in applications.

The study also emphasizes the importance of the LLC resonant network at its particular resonant frequency to achieve optimal efficiency. GaN switches make it possible to operate at higher frequencies, which increases power density and allows for the use of smaller passive components (inductors and capacitors in filter circuits). This is especially advantageous in applications where weight and space are limited. In EV charging systems, where small and effective converters are crucial, this feature is priceless. The inverter that is implemented in the system is a half-bridge as it reduces the current stress on the switches and reduces losses. The Schottky diode is used in a rectifier circuit as it is operable in high switching frequencies and high voltage operability. The simulations are performed in LTSpice software to compare the output power, switching losses, and efficiency at varying frequencies between Silicon and Gallium Nitride as power semiconductor switches in the converter.

For further research in the future on wide band gap and its application in power converters holds a wide range of applications and possibilities, as it is an emerging technology, and exploring its behaviour is very scalable. Thus, it can be conducted on the application of bidirectional converter design for grid-to-vehicle and vehicle-to-grid, in electric vehicle charging converters. The exploration of properties of GaN switches, focusing on the aspects of thermal performance across varying frequencies and the voltage profile, can be studied. Electromagnetic interference is the major issue associated with high frequency. By addressing these issues, a better understanding of the capabilities and constraints of GaN-based converters will be possible, which will be helpful in the creation of more robust, dependable, and efficient power conversion systems for high-power applications like EV charging, extracting renewable energy, and in data centers. These developments are essential to addressing the high demand for efficient and sustainable energy solutions.

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APPENDIX A: SUPPLEMENTARY DATA

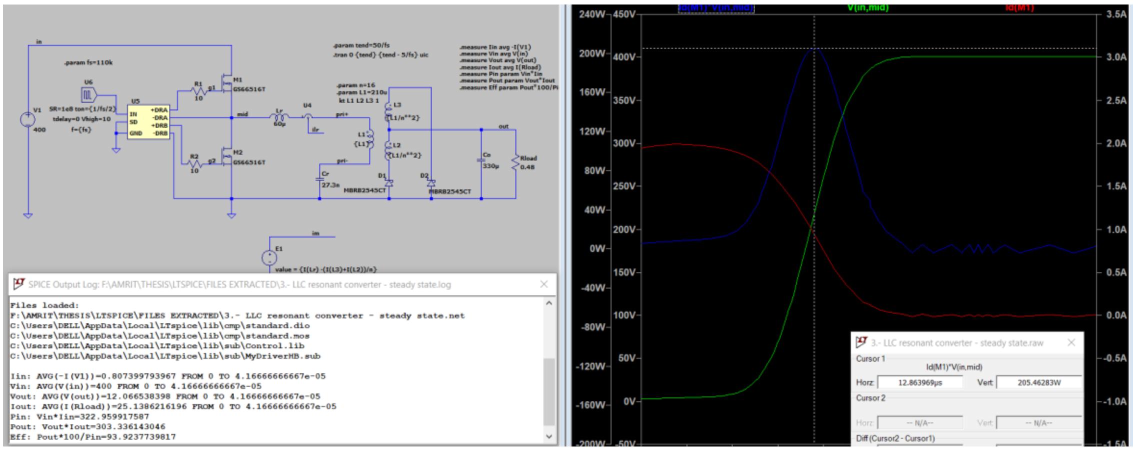
Simulation output data for the Silicon-based switch used in the converter:

Frequency (kHz)	**I(in)**	**I(out)**	**V(out)**	**P(in) (W)**	**P(out) (W)**	**Efficiency (%)**	**Switching Loss (W)**
50	1.23518	22.84427	9.99857	501.4850	228.4167	45.55257	217.78478
75	2.47148	33.30037	24.90141	1003.4234	829.2260	82.64812	8.02246
80	1.78818	31.02688	20.95152	726.0001	650.0604	89.54342	5.31508
85	1.45980	29.55690	18.32161	592.6845	541.5311	91.48877	4.29514
90	1.22032	32.10918	14.28314	495.4501	458.6200	92.58548	3.84124
100	0.74138	20.95537	12.34815	301.0000	258.7603	85.97357	2.46886
110	0.72759	26.60791	10.49650	295.4023	279.2971	94.59972	1.72126
120	0.66956	17.60473	14.45010	271.8454	254.3932	93.65376	3.44430
150	0.53463	17.08972	11.12716	217.0601	190.1601	87.61473	4.32362
200	0.37978	14.01229	10.01466	154.1978	140.3283	91.01184	3.70952

Simulation output data for the Gallium Nitride-based switch used in the converter:

Frequency (kHz)	**I(in)**	**I(out)**	**V(out)**	**P(in) (W)**	**P(out) (W)**	**Efficiency (%)**	**Switching Loss (W)**
50	1.1223165	22.3986	10.7513	455.660	240.814	52.8495717	94.1158
75	2.7202757	46.24399	22.1971	1104.43	971.237	87.94	3.4671
80	2.0898431	40.74909	19.5595	848.476	787.744	92.8422049	2.2973
85	1.7384718	36.93678	17.7296	705.819	654.876	92.7824150	1.85698
90	1.4605703	34.05631	16.3470	592.991	556.719	93.8832106	1.66
100	1.1550949	30.02538	14.4121	468.968	442.111	92.2729847	1.0666
110	0.9448116	27.39166	13.148	383.593	367.817	95.8872783	0.74397
120	0.8200189	25.52717	12.2530	332.927	316.114	94.9500047	1.4887
150	0.6120915	21.91764	10.5204	248.509	230.583	92.7868363	1.8684
200	0.4277849	18.262961	8.766221	173.6807	160.0972	92.1790277	1.603

Losses associated with the switch in the simulation and results shown;



```
.param tend=50/fs
.tran 0 {tend} {tend - 5/fs} uic
.param n=16
.param L1=210u
kt L1 L2 L3 1
.measure Iin avg -I(V1)
.measure Vin avg V(in)
.measure Vout avg V(out)
.measure Iout avg I(Rload)
.measure Pin param Vin*Iin
.measure Pout param Vout*Iout
.measure Eff param Pout*100/Pi
```

SPICE Output Log: F:\AMRIT\THESIS\LTSPICE\FILES EXTRACTED\3.- LLC resonant converter - steady state.log

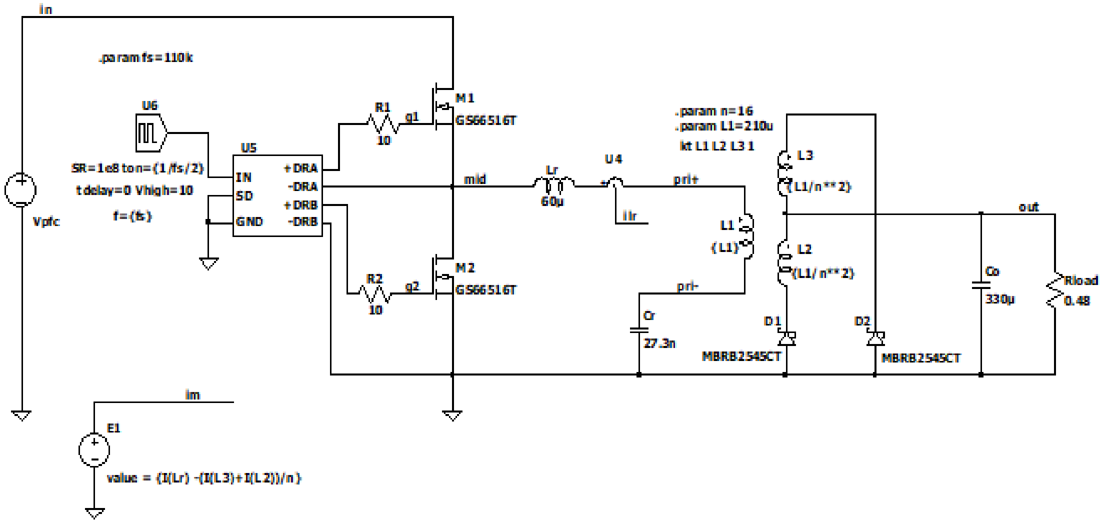
```
Files loaded:
F:\AMRIT\THESIS\LTSPICE\FILES EXTRACTED\3.- LLC resonant converter - steady state.net
C:\Users\DELL\AppData\Local\LTspice\lib\cmp\standard.dio
C:\Users\DELL\AppData\Local\LTspice\lib\cmp\standard.mos
C:\Users\DELL\AppData\Local\LTspice\lib\sub\Control.lib
C:\Users\DELL\AppData\Local\LTspice\lib\sub\MyDriverHB.sub

Iin: AVG(-I(V1))=0.807399793967 FROM 0 TO 4.16666666667e-05
Vin: AVG(V(in))=400 FROM 0 TO 4.16666666667e-05
Vout: AVG(V(out))=12.066538398 FROM 0 TO 4.16666666667e-05
Iout: AVG(I(Rload))=25.1386216196 FROM 0 TO 4.16666666667e-05
Pin: Vin*Iin=322.959917587
Pout: Vout*Iout=303.336143046
Eff: Pout*100/Pin=93.9237739817
```

3.- LLC resonant converter - steady state.raw

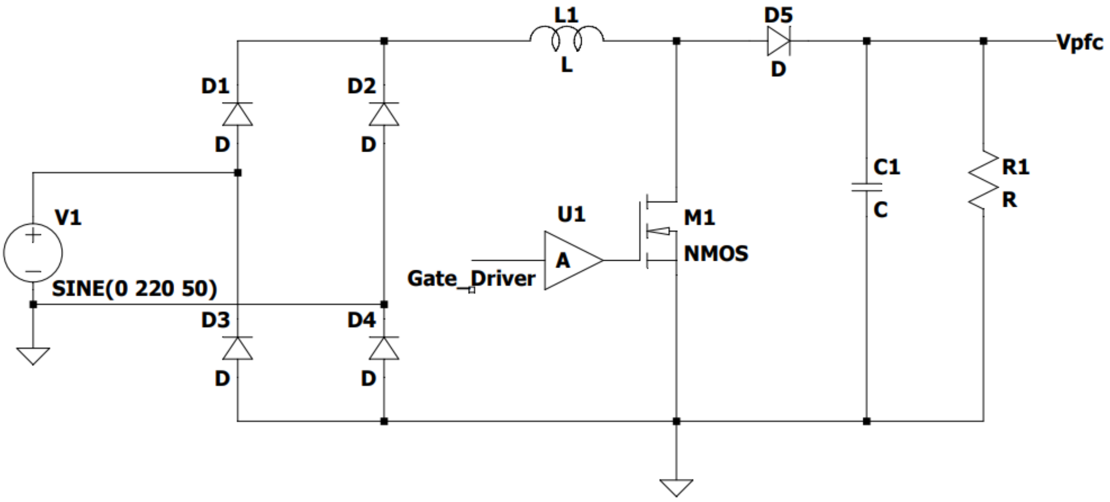
Cursor 1: Id(M1)*V(in,mid)
Horz: 12.863969μs
Vert: 205.46283W

Cursor 2
Horz: -- N/A--
Vert: -- N/A--

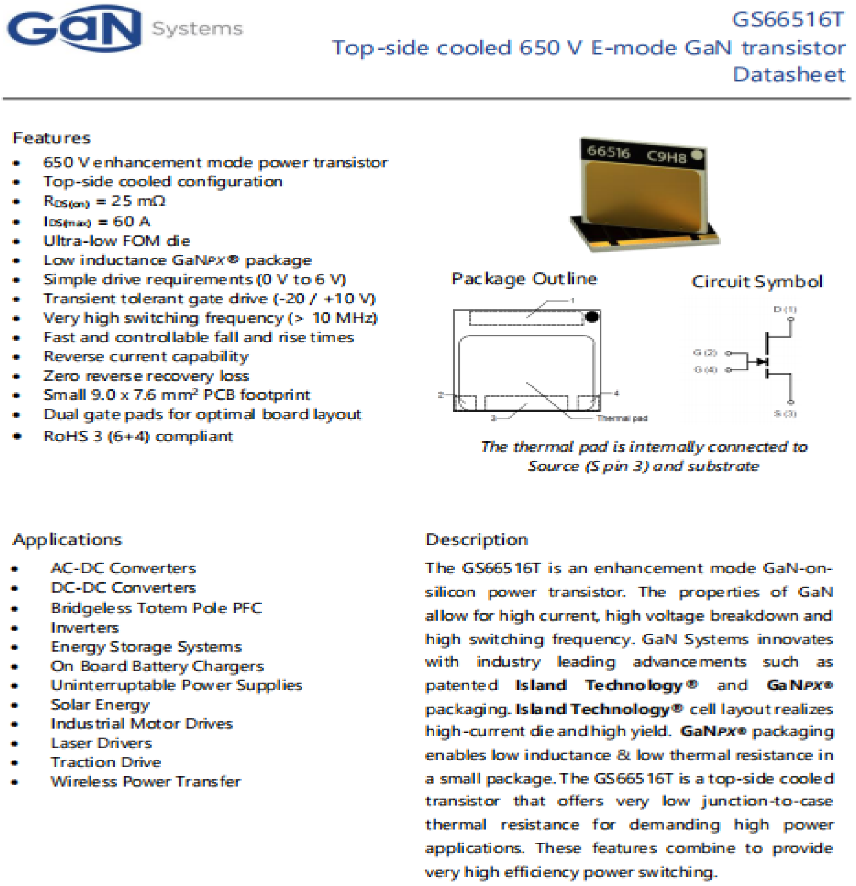
Here’s the simulation diagram of an isolated DC-DC converter in the LTSpice software



Here’s the simulation diagram of an isolated critical boost power factor correction unit in the LTSpice software



Here’s the information about the GaN HEMT and GS66516T information from the datasheet.



GS66516T
Top-side cooled 650 V E-mode GaN transistor
Datasheet

Features

- 650 V enhancement mode power transistor
- Top-side cooled configuration
- $R_{DS(on)}$ = 25 mΩ
- $I_{DS(max)}$ = 60 A
- Ultra-low FOM die
- Low inductance GaN*PX*® package
- Simple drive requirements (0 V to 6 V)
- Transient tolerant gate drive (-20 / +10 V)
- Very high switching frequency (> 10 MHz)
- Fast and controllable fall and rise times
- Reverse current capability
- Zero reverse recovery loss
- Small 9.0 x 7.6 mm² PCB footprint
- Dual gate pads for optimal board layout
- RoHS 3 (6+4) compliant

Package Outline

Circuit Symbol

The thermal pad is internally connected to Source (S pin 3) and substrate

Applications

- AC-DC Converters
- DC-DC Converters
- Bridgeless Totem Pole PFC
- Inverters
- Energy Storage Systems
- On Board Battery Chargers
- Uninterruptable Power Supplies
- Solar Energy
- Industrial Motor Drives
- Laser Drivers
- Traction Drive
- Wireless Power Transfer

Description

The GS66516T is an enhancement mode GaN-on-silicon power transistor. The properties of GaN allow for high current, high voltage breakdown and high switching frequency. GaN Systems innovates with industry leading advancements such as patented **Island Technology®** and **GaN*PX*®** packaging. **Island Technology®** cell layout realizes high-current die and high yield. **GaN*PX*®** packaging enables low inductance & low thermal resistance in a small package. The GS66516T is a top-side cooled transistor that offers very low junction-to-case thermal resistance for demanding high power applications. These features combine to provide very high efficiency power switching.

Absolute Maximum Ratings (T_{case} = 25 °C except as noted)

Parameter	Symbol	Value	Unit
Operating Junction Temperature	T_J	-55 to +150	°C
Storage Temperature Range	T_S	-55 to +150	°C
Drain-to-Source Voltage	V_{DS}	650	V
Transient Drain-to-Source Voltage (Note 1)	$V_{DS(transient)}$	750	V
Gate-to-Source Voltage	V_{GS}	-10 to +7	V
Gate-to-Source Voltage - transient (Note 1)	$V_{GS(transient)}$	-20 to +10	V
Continuous Drain Current (T_{case}=25 °C)	I_{DS}	60	A
Continuous Drain Current (T_{case}=100 °C)	I_{DS}	47	A
Pulse Drain Current (Pulse width 50 µs, V_{GS} = 6 V) (Note 2)	$I_{DS\ Pulse}$	120	A

(1) For ≤ 1 µs

(2) Defined by product design and characterization. Value is not tested to full current in production.

Electrical Performance Graphs

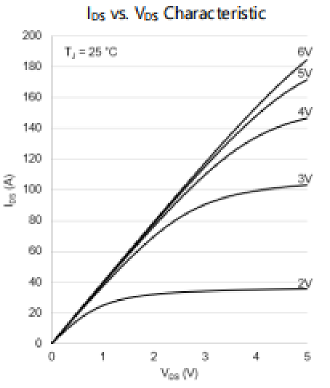


Figure 1: Typical I_{DS} vs. V_{DS} @ T_J = 25 °C

Electrical Performance Graphs

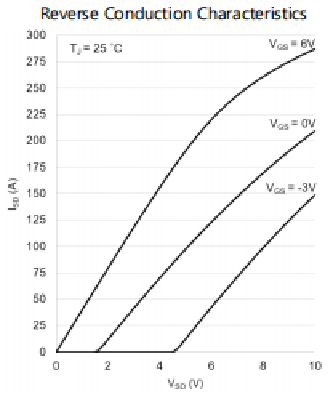


Figure 9: Typical I_{SD} vs. V_{SD} (T_J = 25 °C)

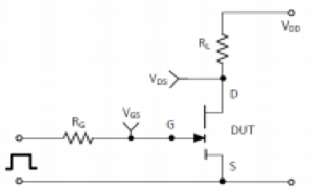


Figure 16: switching time test circuit

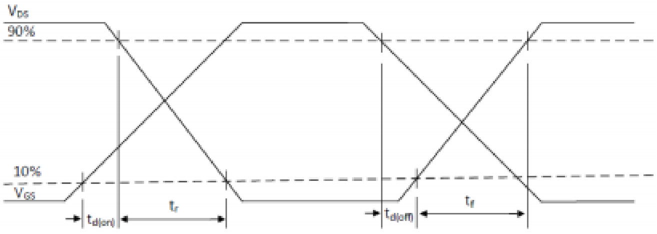
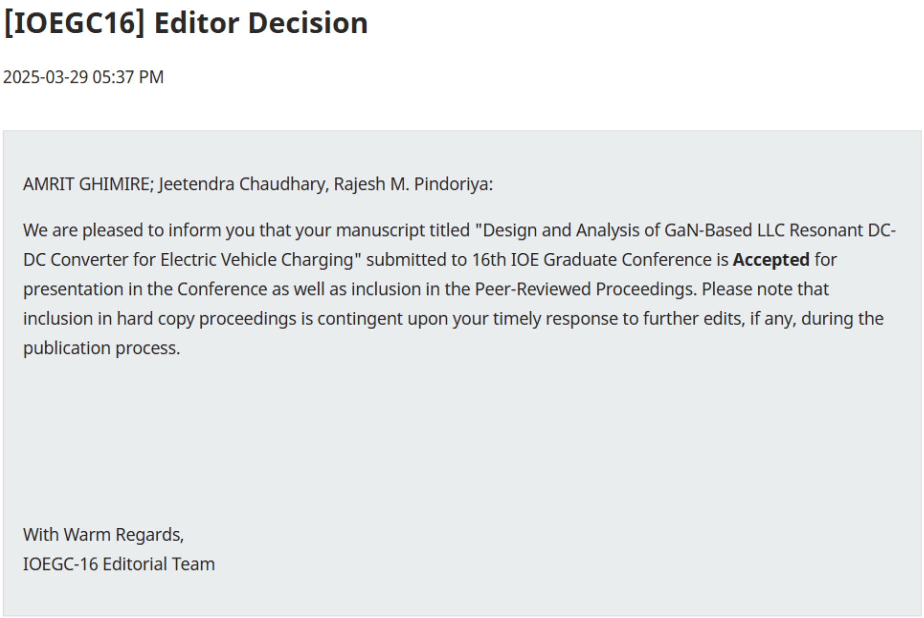


Figure 17: switching time waveforms

APPENDIX B: PUBLICATION

Paper Acceptance Notification in IOEGC:



[IOEGC16] Editor Decision

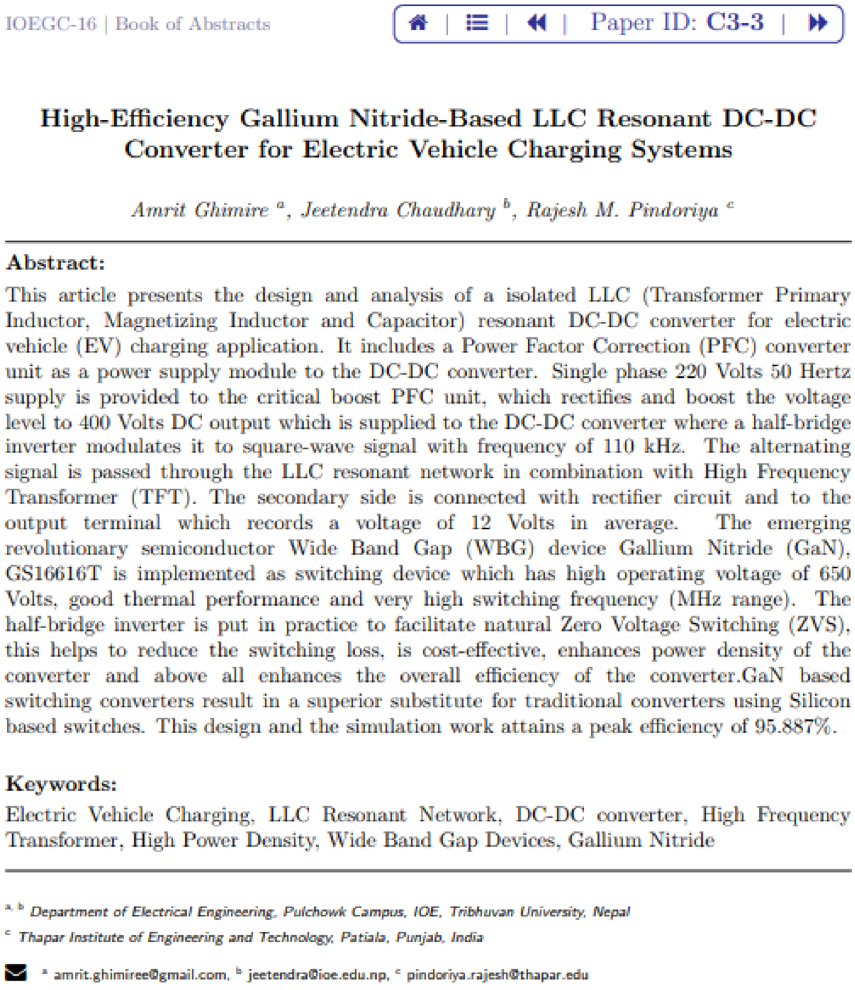
2025-03-29 05:37 PM

AMRIT GHIMIRE; Jeetendra Chaudhary, Rajesh M. Pindoriya:

We are pleased to inform you that your manuscript titled "Design and Analysis of GaN-Based LLC Resonant DC-DC Converter for Electric Vehicle Charging" submitted to 16th IOE Graduate Conference is **Accepted** for presentation in the Conference as well as inclusion in the Peer-Reviewed Proceedings. Please note that inclusion in hard copy proceedings is contingent upon your timely response to further edits, if any, during the publication process.

With Warm Regards,
IOEGC-16 Editorial Team

Abstract published in the IOEGC;



IOEGC-16 | Book of Abstracts

Paper ID: **C3-3**

High-Efficiency Gallium Nitride-Based LLC Resonant DC-DC Converter for Electric Vehicle Charging Systems

Amrit Ghimire [a], *Jeetendra Chaudhary* [b], *Rajesh M. Pindoriya* [c]

Abstract:

This article presents the design and analysis of a isolated LLC (Transformer Primary Inductor, Magnetizing Inductor and Capacitor) resonant DC-DC converter for electric vehicle (EV) charging application. It includes a Power Factor Correction (PFC) converter unit as a power supply module to the DC-DC converter. Single phase 220 Volts 50 Hertz supply is provided to the critical boost PFC unit, which rectifies and boost the voltage level to 400 Volts DC output which is supplied to the DC-DC converter where a half-bridge inverter modulates it to square-wave signal with frequency of 110 kHz. The alternating signal is passed through the LLC resonant network in combination with High Frequency Transformer (TFT). The secondary side is connected with rectifier circuit and to the output terminal which records a voltage of 12 Volts in average. The emerging revolutionary semiconductor Wide Band Gap (WBG) device Gallium Nitride (GaN), GS16616T is implemented as switching device which has high operating voltage of 650 Volts, good thermal performance and very high switching frequency (MHz range). The half-bridge inverter is put in practice to facilitate natural Zero Voltage Switching (ZVS), this helps to reduce the switching loss, is cost-effective, enhances power density of the converter and above all enhances the overall efficiency of the converter.GaN based switching converters result in a superior substitute for traditional converters using Silicon based switches. This design and the simulation work attains a peak efficiency of 95.887%.

Keywords:

Electric Vehicle Charging, LLC Resonant Network, DC-DC converter, High Frequency Transformer, High Power Density, Wide Band Gap Devices, Gallium Nitride

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[c] *Thapar Institute of Engineering and Technology, Patiala, Punjab, India*

✉ [a] amrit.ghimiree@gmail.com, [b] jeetendra@ioe.edu.np, [c] pindoriya.rajesh@thapar.edu

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Tribhuvan University
इन्जिनियरिङ्ग अध्ययन संस्थान
Institute of Engineering
थापाथली क्याम्पस
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Website: www.tcioe.edu.np
गोश्वारा पो. नं. २८०, थापाथली, काठमाडौं
फोन: ०१-५३३९७६६

Date: April 21, 2025

To Whom It May Concern:

This is to certify that the paper titled **"High-Efficiency Gallium Nitride-Based LLC Resonant DC-DC Converter for Electric Vehicle Charging Systems"** (Submission# **519**) submitted by **AMRIT GHIMIRE** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 16th IOE Graduate Conference held during April 18 - 20, 2025. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.

Chaulagain

Dr. Raj Kumar Chaulagain,
Convener,
16th IOE Graduate Conference

IOE Graduate Conference

Certificate of Participation

THIS CERTIFICATE IS AWARDED TO

Amrit Ghimire

in recognition of an invaluable contribution as

PAPER PRESENTER

at the 16th IOE Graduate Conference

Organized by Tribhuvan University, IOE, Thapathali Campus in association with IOE, Office of the Dean held from April 18-20, 2025 at Thapathali Campus, Kathmandu, Nepal.

Dr. Raj Kumar Chaulagain
Convener
16th IOE Graduate Conference

Dr. Khem Gyanwali
Campus Chief
Thapathali Campus

Prof. Dr. Sushil Bahadur Bajracharya
Dean
Institute of Engineering

High-Efficiency Gallium Nitride-Based LLC Resonant DC-DC Converter for Electric Vehicle Charging Systems

Amrit Ghimire [a], Jeetendra Chaudhary [b], Rajesh M. Pindoriya [c]

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[c] *Thapar Institute of Engineering and Technology, Patiala, Punjab, India*
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Abstract

This article presents the design and analysis of a isolated LLC (Transformer Primary Inductor, Magnetizing Inductor and Capacitor) resonant DC-DC converter for electric vehicle (EV) charging application. It includes a Power Factor Correction (PFC) converter unit as a power supply module to the DC-DC converter. Single phase 220 Volts 50 Hertz supply is provided to the critical boost PFC unit, which rectifies and boost the voltage level to 400 Volts DC output which is supplied to the DC-DC converter where a half-bridge inverter modulates it to square-wave signal with frequency of 110 kHz. The alternating signal is passed through the LLC resonant network in combination with High Frequency Transformer (TFT). The secondary side is connected with rectifier circuit and to the output terminal which records a voltage of 12 Volts in average. The emerging revolutionary semiconductor Wide Band Gap (WBG) device Gallium Nitride (GaN), GS16616T is implemented as switching device which has high operating voltage of 650 Volts, good thermal performance and very high switching frequency (MHz range) . The half-bridge inverter is put in practice to facilitate natural Zero Voltage Switching (ZVS), this helps to reduce the switching loss, is cost-effective, enhances power density of the converter and above all enhances the overall efficiency of the converter.GaN based switching converters result in a superior substitute for traditional converters using Silicon based switches. This design and the simulation work attains a peak efficiency of 95.887%

Keywords

Electric Vehicle Charging, LLC Resonant Network, DC-DC converter, High Frequency Transformer, High Power Density, Wide Band Gap Devices, Gallium Nitride

1. Introduction

With the accelerating proliferation and active penetration of electric vehicles (EV) in today's automotive market, the significance of descent charging technology and infrastructure is demanding along with the requisition of higher efficiency and high power density devices. Furthermore, with the increased demand for fast charging to increase range anxiety and less charging time, the demand for good charging technology is increased [1]. The sudden automotive market shift from internal combustion (IC) engine locomotives to electric vehicles has considerable economic, environmental, and ecological benefits due to cost- effectiveness and net-zero carbon emission [2].

This paper discusses the application of Advanced Electric Vehicle charging technology, with better efficiency and compatibility. An improvised noiseless boost Power Factor Correction (PFC) along with DC-DC converter design helps to generate required output voltage level in order to charge the rated batteries. A boost PFC circuit is designed to convert the available AC source in our residence to a DC source acting as a rectifier, increasing the voltage to required voltage level and helps to enhance the power quality by reducing Total Harmonic Distortions (THD) and Electromagnetic Interference (EMI). DC-DC converters improve safety and efficiency through isolated topology, allowing bidirectional energy flow during charging and regeneration braking. Most important, the converter works to maintain a stable output voltage level.[3].

A 220 Volts Alternating Current (AC) from residential power socket is supplied to the critical boost PFC converter circuit, which rectifies the AC signal and boost the voltage level to 400 Volts. The output of PFC is fed to the half-bridge inverter of the isolated LLC resonant DC-DC converter, which ultimately reduces the voltage level to 12 volts. A half-bridge inverter with Gallium Nitride (GaN) as a switching devices is used in the first stage to convert the DC voltage into high frequency AC signal generation which is further transferred to the rectifier circuit through isolated high frequency transformer to convert back to DC required voltage level.

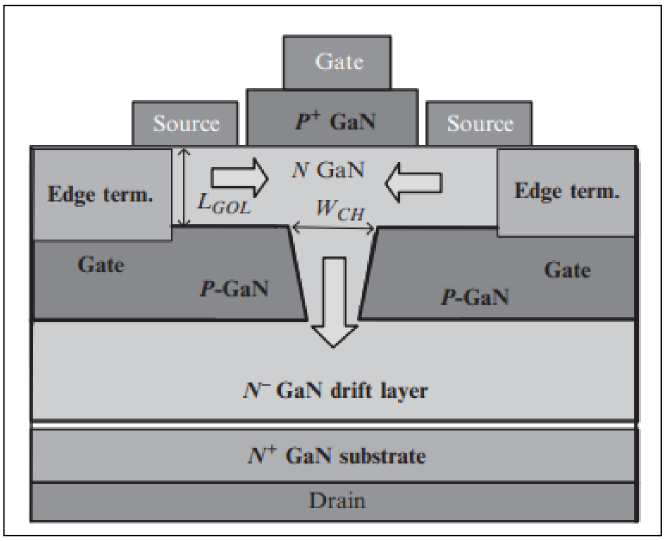

Figure 1: A cross section of a lateral channel GaN JFET with a vertical drift region

Power electronics is currently being revolutionized by the emergence of Wide Band Gap (WBG) devices such as Gallium Nitride (GaN) and Silicon Carbide (SiC) as cutting-edge semiconductor devices with superior thermal performance, higher operating voltage, very high switching frequency and low on-state resistance, creating a possibility for highly efficient, compact design, and future-oriented energy conversion technologies in power electronics [4]. Fig.1 depicts the cross sectional diagram of GaN,along with internal structures. Gallium Nitride (GaN) has high electron mobility for low on-state losses, high frequency switching in the range of Mega Hertz and normal operating voltage of 650 volts. Similarly, Silicon Carbide (SiC) operate at 1,200 V and 300 kHz. It performs exceptionally well thermally and efficiently in high-power applications (such as in MW-scale converters) . Compared to Si-based semiconductor devices, both Wide Band Gap (WBG) semiconductor devices has good improvement in reliability, compact designs, and reduction in energy losses. The general comparison on current density on application of voltage is illustrated in Fig.2. And, due to mentioned cutting-edge attributes, a Gallium Nitride-based semiconductor device is proposed for this application.

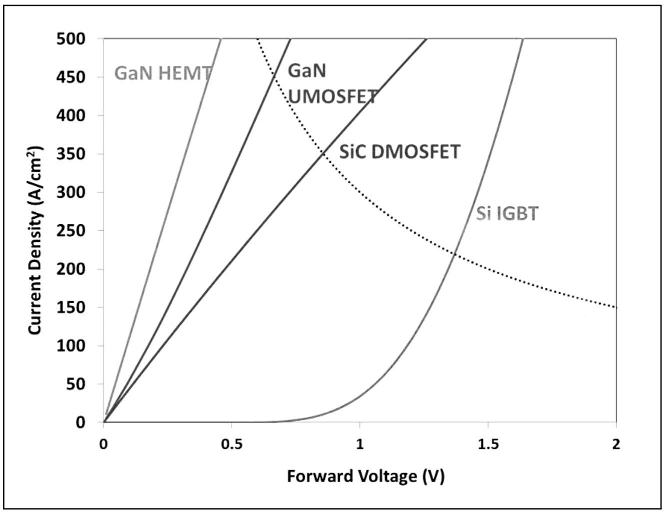

Figure 2: A comparison among Si, Sic and GaN Current Density versus forward voltage

2. Proposed GaN Based Converter Topology

2.1 Wide Band Gap Devices (WBG)

Wide Band Gap (WBG) Devices are semiconductor devices which are made from materials with a higher energy gap between valence band and conduction band in the atom in comparison with traditional Silicon (Si) based semiconductors. These WBG devices are Silicon Carbide (SiC) and Gallium Nitride (GaN), which have energy bandgap of around 3.3 eV and 3.4 eV , respectively, while a Silicon has a bandgap of 1.1 eV [5, 6]. The mateirals in thesse devices enables to operate at higher voltage level (up to 10 kV range), has elevated operating temperature limit(200–300°C) [7], and can attain a very fast switching frequency (upto MHz range). Gallium Nitride are quite familier material to us as it was being used in energy efficient LED lightsm Blu-ray players, and in power efficient military/ aeronautical systems like radar. And after founding its peculiar behaviour, these devices are now applicable in power electronics scenarios such as, electric vehicles charging, solar inverters, data centers converters, aerospace systems, and even in fast chargers for cell phones. And WBG devices are capable of creating this demand and interest due to their ground-breaking performance specifically due to their high thermal stability, low energy losses, and low on-state resistance [8].

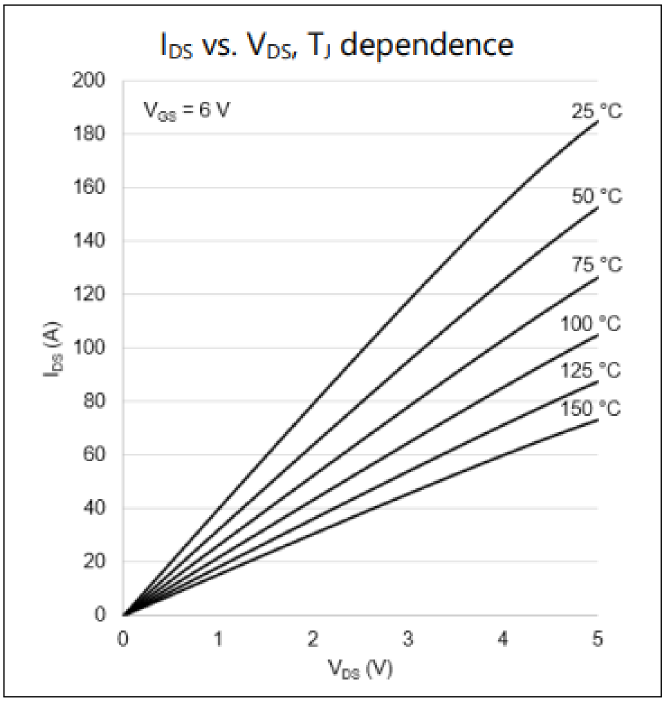

Figure 3: Nature of drain-to-source current versus drain-to-source voltage depending on the temperature range

The Gallium Nitride devices are typically used for medium voltage applications as it deals with voltage level of around 600 volts and compararatively higher switching frequency. Commercially, GaN switches of 650 Volts is available from companies like Infineon, Wolfspeed, etc. A Its heat/ radiation resistance and eco-friendly profile, reducing energy usage and pollution and recently it is discovered as a semiconductor for next generation chips and is called as "Ultimate Semiconductor Material".This application uses a GaN model, GS66516T from Infineon. Given Fig.3 and Fig.4 depicts the Changing nature of drain-to-source current versus drain-to-source voltage of GaN device depending on the temperature range from 25 °C to 150 °C and transientnature of thermal impedance, respectively.

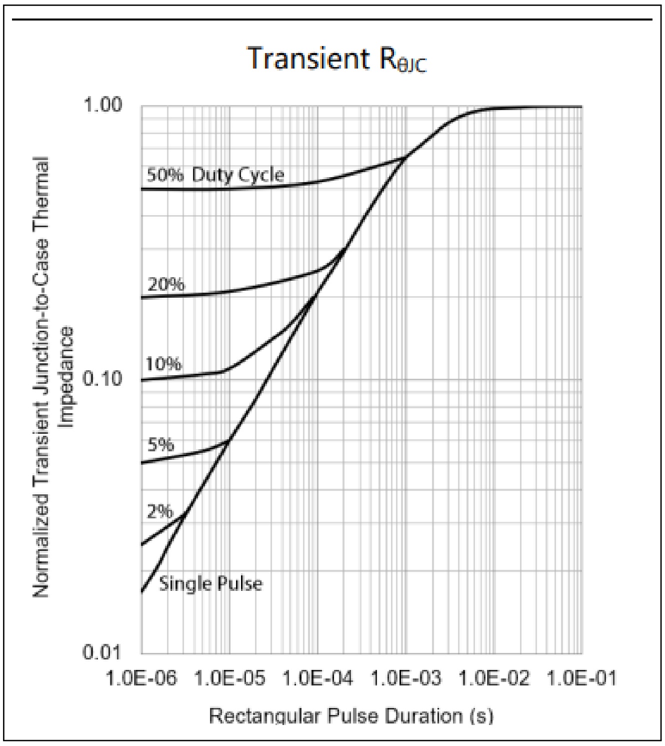

Figure 4: Transient nature dependence with thermal impedance

2.2 DC-DC Converter

DC-DC converters are fundamental power conversion devices consisting of a rectifier and inverter circuit. Ther major objective of these converter is to convert a unsteady input voltage to a desired output voltage level to supply balanced and reliable power source to various kinds of load. The power generation from renewable sources has ongoing fluctuations in power generation causing turbulence in output voltage and frequency. In order to obtain stable output power, a converter combination of inverter and rectifier along with suitable filter circuit (like, capacitor and inductor circuit).

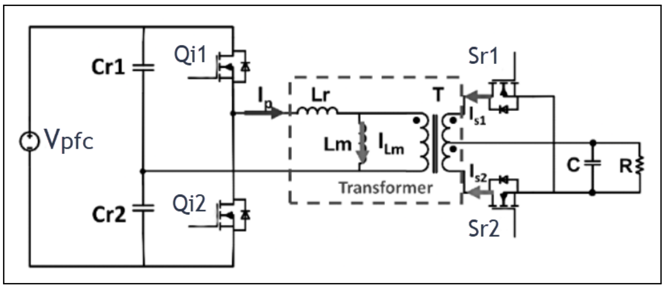

Figure 5: LLC resonant converter topology

The DC-DC converter is also used widely in other applications like DC motor driver systems, communication systems and medical electronics. Moreover, the expected features of a DC-DC converter includes easy control mechanism, capability to reduce electromagnetic interference (EMI) noises, and decreasing switching losses [9]. In general DC-DC converter are of two types, isolated and non-isolated. Isolated converter generally use High Frequency Transformer or sometime opto-couplers to islolate between the source and the load. In our application we have used isolated DC-DC converter of step down nature to obtain a regulated output voltage of 12 volts and a isolation is provided by high frequency transformer of 110 KHz.

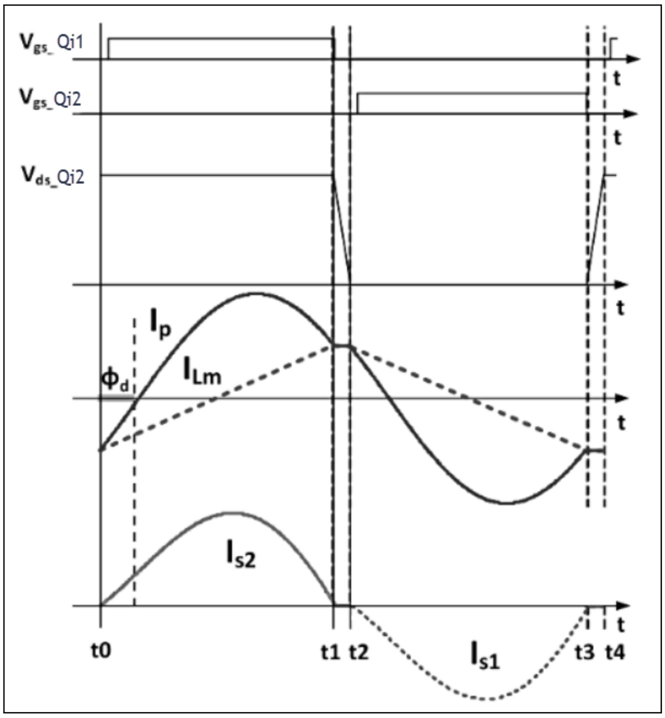

Figure 6: LLC resonant converter waveforms at the resonance frequency

2.3 Relationships Among the Device Parameters

The LLC resonant half-bridge converter topology is shown in Fig. 5, and the waveforms of converter at resonance are shown in Fig. 6. During the dead time (t_1 to t_2), the drain to source voltage of Qi_2 drops to zero due to the magnetizing current I_{L_m} that discharges the output capacitance of the device. Qi_2 then turns on with zero voltage switching.

For ZVS to occur, peak magnetizing current and dead time are sufficiently required in order to discharge parasitic capacitance and that also includes primary and secondary device output capacitance and transformer winding capacitance [10]. During dead time (t_1 to t_2), the magnetizing inductance acts as a current source. The Zero voltage switching charge balance equation for primary side half bridge topology is given by:

$$I_{L_{m-\mathrm{pk}}} T_d = 2C_{\mathrm{pri\_oss}} V_{\mathrm{in}} + C_w V_{\mathrm{in}} + \frac{1}{N} \cdot 2nC_{\mathrm{sec\_oss}} \cdot 2V_o \tag{1}$$

where:

- $I_{L_{m-\mathrm{pk}}}$ = peak magnetizing current,
- T_d = dead time,
- $C_{\mathrm{pri\_oss}}$ = primary-side device output capacitance,
- $C_{\mathrm{sec\_oss}}$ = secondary-side device output capacitance,
- C_w = transformer winding capacitance (referred to primary),
- n = number of secondary-side parallel devices,

- N = transformer turns ratio,
- V_{in} = input voltage,
- V_o = output voltage.

The turns ratio of the transformer is given by

$$N = \frac{V_{\text{in}}/2}{V_o} \tag{2}$$

Considesing current waveform from (t_0 to t_1), in Fig.6, the peak magnetizing current is given by

$$I_{L_{m-\text{pk}}} = \frac{NV_o\left(\frac{T_s}{2} - T_d\right)}{2L_m} \tag{3}$$

Combining (1), (2), and (3), the magnetizing inductance becomes

$$L_m = \frac{T_d\left(\frac{T_s}{2} - T_d\right)}{4\left(2C_{\text{pri\_oss}} + \frac{1}{N^2} \cdot 2nC_{\text{sec\_oss}} + C_w\right)} \tag{4}$$

The secondary side current I_{s1} or I_{s2} equals the primary side current I_p minus I_{L_m} [10]. And the average secondary current after rectification can be computed as

$$N \cdot \frac{2}{T_s}\int_0^{\frac{T_s}{2}-T_d} (I_p - I_{L_m})\, dt = \frac{V_o}{R_L} \tag{5}$$

$$\tag{6}$$

The primary-side RMS current is given by

$$I_{\text{rms\_P}} = \sqrt{\frac{V_o^2 T_s^2 \pi^2}{8R_L^2 N^2 (T_s - 2T_d)^2} + \frac{1}{2} I^2_{L_{m-\text{pk}}}} \tag{7}$$

Including the magnetizing current during dead time, the total primary RMS current is given by

$$I_{\text{rms\_P\_total}} = \sqrt{\frac{V_o^2 T_s^2 \pi^2}{8R_L^2 N^2 (T_s - 2T_d)^2} + \left(\frac{1}{2} + \frac{2T_d}{T_s}\right) I^2_{L_{m-\text{pk}}}} \tag{8}$$

The secondary-side RMS current is given by

$$I_{\text{RMS\_S\_total}} = N\sqrt{\frac{T_s - 2T_d}{2T_s}}\left[I^2_{\text{RMS\_P}} + \left(\frac{1}{3} - \frac{8}{\pi^2}\right) I^2_{L_{m-\text{pk}}}\right] \tag{9}$$

From (8) and (9), it can be seen that the dead time and the peak magnetizing current impacts both primary and secondary RMS currents. Large dead times or peak currents increase conduction losses and results in inefficient energy transfer. Therefore, small peak magnetizing current, small dead time and the overall device capacitance that take part during the dead times ought to be minimum [10].

Table 1: LLC Resonant DC-DC CONVERTER SPECIFICATIONS

Parameter	**Value**
Power rating	330 W
Input voltage	400 VDC
Output voltage	12 VDC
Switching frequency	110 kHz

2.4 Zero Voltage Switching (ZVS) Operation

Zero Voltage Switching is a soft-switching technique where a power semiconductor device is turned on or turned off when voltage across its terminals is zero or near zero. This eliminates switching losses during the fast switching operation whereas there is high switching loss during hard switching. ZVS minimizes switching losses by ensuring the device voltage drops to zero before turn-on. The LLC resonant tank comprises the resonant inductor, magnetizing inductor, and resonant capacitor, magnetizing current acts as a current source during dead time to discharge parasitic capacitance. GaN devices used in the application enhances ZVS due to their low output capacitance. ZVS eliminates voltage current overlap during turn-on which is critical for high frequency operation. Lower losses is also applicable for compact designs of the device along with reduced cooling requirements.

3. Design of Proposed GaN isolated DC-DC Converter

The proposed GaN-based isolated DC-DC converter is designed and simulated in LTSpice software and the design incorporates noiseless critical boost Power Factor Correction unit, Half-bridge Inverter circuit connected with LLC resonant network, a high frequency transformer and a rectifier circuit as major components. The commonly available voltage level of 220 Volts is taken as input for the PFC converter and it boost the voltage level to 400 volts [11]. This same voltage level is fed to the half-bridge inverter of the DC-DC Converter. The PFC converter topology is shown in Fig.7. The switches used in the inverter is a Gallium Nitride 650 volts, GS66516T. The GS66516T is an enhancement mode GaN-on-silicon power transistor . The properties of GaN allows for high current, high voltage breakdown and high switching frequency. This is a top-side cooled transistor that offers very low junction-to-case thermal resistance for demanding high power applications [7]. These features combine to provide very high efficiency power switching.

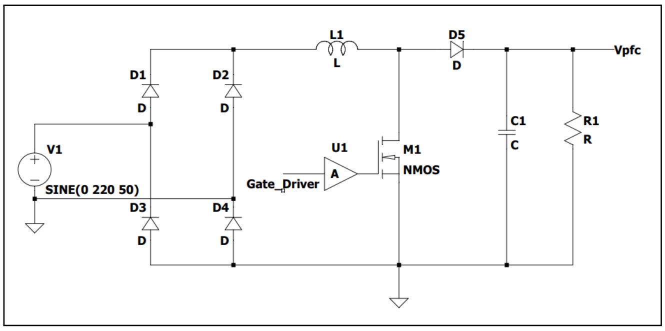

Figure 7: Schematic diagram of PFC Converter in LTSpice

PFC converter parameters are presented below

f_s = Source frequency (Hz)

C = Filter capacitance (Farads)

$F_{\max}$ = Maximum switching frequency (Hz)

V_{Pfc} = Output Voltage (Volts)

V_1 = Source Voltage (Volts)

R_1 = Load Resistance (Ohms)

L_1 = Converter Inductor (Henries)

$F_{\min}$ = Minimum switching frequency (Hz)

$\hat{V}_0$ = Output ripple voltage (Volts)

The on-time period of the switches is given by

$$T_{0N} = \frac{1}{F_{\max}}$$

The output voltage of the PFC converter is given by

$$V_{\text{Pfc}} = V_1 \cdot \sqrt{R_1} \cdot \frac{4 \cdot L_1}{T_{0N}}$$

Minimum possible operating frequency can be calculated from this equation

$$F_{\min} = \frac{1}{T_{0N}} \left(1 - \frac{V_1}{V_0} \right)$$

There is a ripple voltages remaining as AC components and harmonics persists in the output, 1 % of output voltage is considered as ripple quantity.

$$\hat{V}_0 = 1\% \text{ of } V_0$$

The filter capacitance is given by

$$C = \frac{P_1}{4\pi \cdot V_0 \cdot \hat{V}_0 \cdot f_s}$$

Table 2: PFC Converter parameters

Parameter	Value
Source Voltage	220 Volts
Source Frequency	50 Hz
Inductor	1.32 mH
Switching frequency (max)	200 kHz
Switching frequency (min)	37.4 kHz
Switch On time (Ton)	.05 mSec
Output Voltage	400 Volts

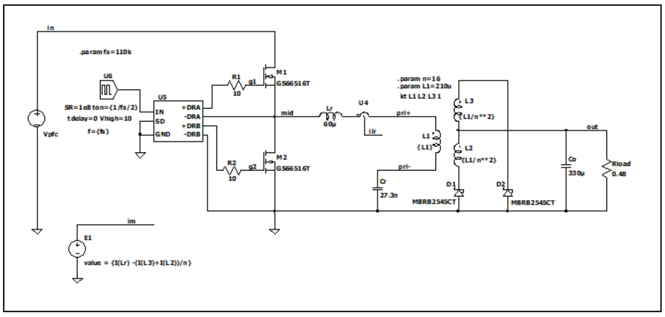

Figure 8: Schematic diagram of DC-DC Converter in LTSpice

Sequentially, DC-DC converter has special design requirement of a half-bridge inverter, a LLC resonant network incorporating high frequency transformer isolating it with a synchronous rectifier circuit and a battery or a load. A Half-bridge inverter is preferred in this application rather than other configuration as this configuration simplifies the network, and makes it cost-effective, efficient and suitable in high frequency and moderate power scenario. Half-bridge naturally supports ZVS operation in LLC converter, having lower switches is obviously a cost effective, and reduces the switching loss and gate drive complexity is reduced by this phenomenon [12]. The switches used in the inverter is Gallium Nitride (GaN) 650 volts, GS66516T. The GS66516T is an enhancement mode GaN-on-silicon power transistor. The characteristics are presented in Table 3. The LLC resonant converter of DC-DC converter that operates based on the resonance of the inductor (L) and capacitor (C) components, typically consisting of a half-bridge or full-bridge inverter, a resonant tank (comprising resonant inductor (L), resonant capacitor (C), and magnetizing inductor (Lm), a transformer, and rectifier circuits on the secondary side. One of the main advantages of the LLC resonant converter is its ability to achieve Zero Voltage Switching (ZVS) for primary-side switches and Zero Current Switching (ZCS) for secondary-side rectifiers, which reduces switching losses and enhances efficiency, especially at high frequency operation. Operating at around 110 KHz allows for maximum efficiency and this allows to use smaller passive components (inductors and capacitors) resulting in contribution to achieve higher power density and reduced weight and size of the converter. The transformer in an LLC resonant converter plays a crucial role, not only for voltage transformation but also as part of the resonant network, with the magnetizing inductance (Lm) of the transformer utilized as part of the resonant tank to help achieve soft switching [10].

Table 3: Infineon GS66516T Configuration

Parameter GS66516T	Value
Voltage Level	650 Volts
On Resistance	25 m Ohm
Maximum Drain-to-Source current	60 A
Drive voltage requirement	(o to 6 Volts)
Switching frequency (max)	10 MHz
Operating junction temperature	-55 °C to +150 °C
Reverse Recovery Loss	0 Watts

4. Result and Analysis

From the simulation of the LLC resonant DC DC converter, following observation can be made in the PFC circuit followed by DC-DC Converter.

Fig.9 is the representation of input AC sinusoidal voltage of magnitude 311 Volts and a output DC voltage of 420 Volts.

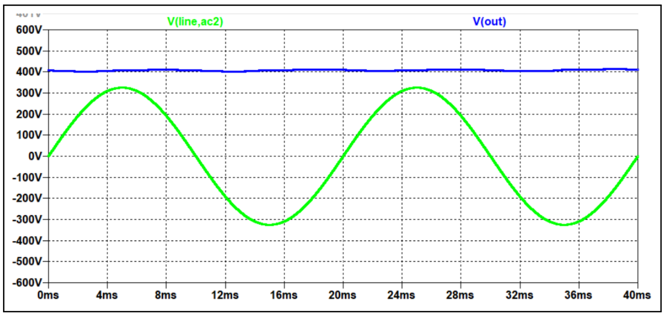

Figure 9: Input and output voltage of PFC converter

Fig.10 shows the input and output voltage waveform of a DC-DC converter, which shows around 406 Volts of DC supply from the PFC unit and around 13 Volts of output power at resonant frequency of 110 kHz.

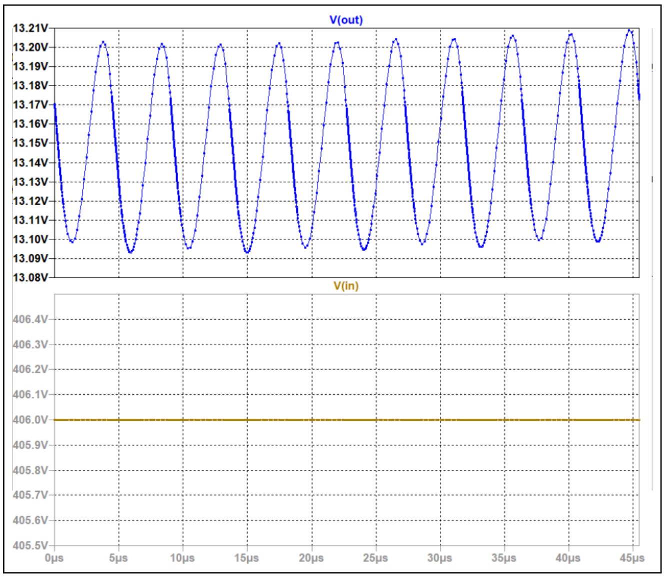

Figure 10: Input and output voltage waveform of DC-DC Converter

The characteristic waveforms of GaN switches is represented in the Fig.11.

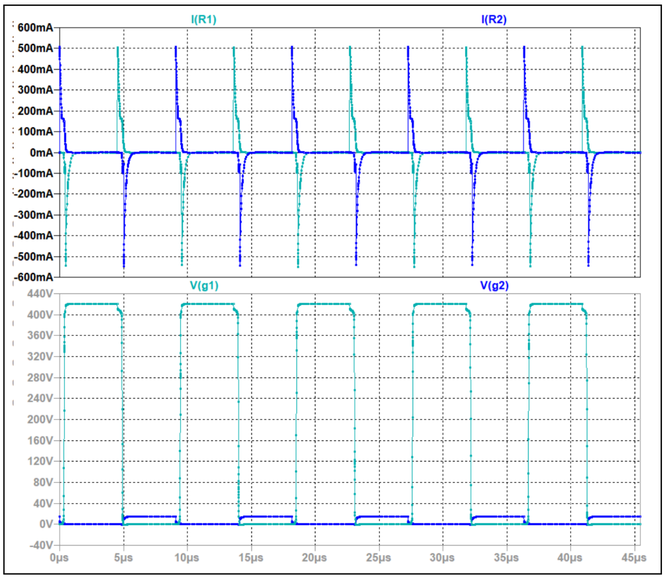

Figure 11: GS66516T GaN switch current and voltage waveform for DC-DC converter

The primary and secondary voltage and current levels are represented by the Fig.12. The graph between frequency and efficiency is plotted in Fig.13 and Output power versus frequency is plotted in Fig.14.

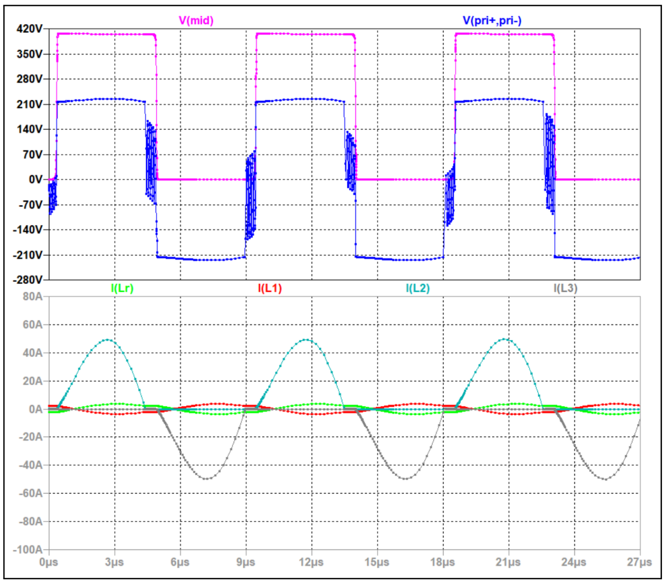

Figure 12: Primary and Secondary current and voltage of transformer in DC-DC Converter

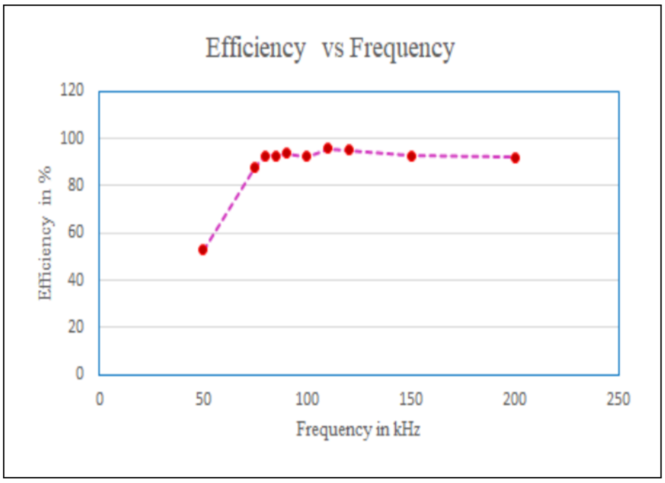

Figure 13: Frequency vs Efficiency graph

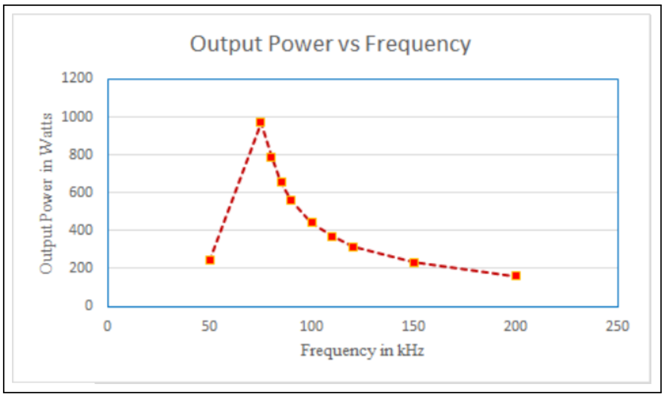

Figure 14: Output power vs frequency graph

This simulation in overall explains that the output voltage obtaied is stable and regular with minimum harmonics and ripples, the maximum efficiency achieved is 95.8872782975 % with output power of 360.1455 Watts, output voltage of 13.14 Volts.

5. Conclusion

The Gallium Nitride based LLC resonant DC-DC converter for electric vehicle charging is simulated in LTSpice software and result were analyzed based on the result obtained. This simulation depicts that the maximum efficiency obtained is 95.8872782975 % with output power of 360.1455 Watts, output voltage of 13.14 Volts. While supplying the varying frequency switching operation the maximum efficiency was considered and it was maximum when switching frequency is 110 kHz. This points out a scenario that at a particular resonance frequency of a LLC resonant network, a converter gives the maximum efficiency performance and a Gallium Nitride switches do contribute in achieving high efficient, enhances power density as passive filter devices are comparatively small and less due to higher frequency operation. Such type of high efficient converter can be widely used where there is a need of reliable and constant DC power source. Using the same reference, we can also obtain the varying voltage range by tuning the inductance level of high frequency transformer and duty cycle of the GaN switch operation. Furthermore, GaN and wide band gap devices uses in a converter has a huge room for finding new characteristics and behaviour, losses that occur in the switches, thermal behaviour change with change in frequency and voltage can be explored.

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APPENDIX C: PLAGIARISM TEST REPORT

Amrit Ghimire

Design and Analysis of Gallium Nitride-based LLC Resonant DC-DC Converter

Tribhuvan University

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