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Ultra-High-Frequency Soft-Switched DC–DC Converter Using Hybrid SiC–GaN Architecture for Next-Generation Electric Vehicle Powertrains

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ABSTRACT

The design of an efficient hybrid DC-DC converter (SiC-GaN) for future use in ultra-high frequency DC-DC converters of next generation electric vehicle (EV) powertrains has been presented in this document. The proposed topology combines the benefits of high-voltage handling of silicon carbide (SiC) devices, with the benefits of high-speed switching that gallium nitride (GaN) devices provide, by using both materials in one device. The method for achieving zero voltage switching (ZVS), together with near zero current switching (ZCS), caused the switching losses at high operating frequencies (i.e., 500 kHz to 1 MHz) to be dramatically lower than conventional approaches to ZVS, ZCS converters. Initial theoretical models were developed to design and analyze the converter, which was then verified through simulation as well as through the construction of a prototype 300 W converter to test and evaluate its ability to meet these performance specifications. Experimental performance confirmed that the hybrid converter functioned over an operating range of 500 kHz to 1 MHz, producing stable performance characteristics throughout the entire range. In particular, during operation at approximately 80 percent load, a peak efficiency of 97.6 percent was achieved. In addition, over the entire operating range of the converter, efficiencies greater than 96.5 percent were consistently achieved. The use of hybrid SiC and GaN devices reduced switching losses compared to traditional Si and SiC converters; in addition, hybrid devices provided for improved thermal distribution throughout the devices. The operation of a converter at high frequencies significantly reduced the size of passive components, resulting in both improved power density and the overall reduction in size of the entire DC/DC converter assembly. Through the results reported in this study, it has been demonstrated that a hybrid SiC-GaN architecture can provide an effective and efficient solution for high-performance EV applications, offering performance trade-offs among reliability, compactness and efficiency.

Keywords: *Hybrid SiC–GaN Converter; DC–DC Converter; Ultra-High-Frequency Switching; Soft-Switching; Electric Vehicle Powertrain; Wide Bandgap Semiconductors; Power Density; Switching Loss Reduction; Resonant Converter; High-Efficiency Power Conversion.*

1. INTRODUCTION

The rise in the use of electric cars has led to a robust increase in demand for compact, high- performance power devices with high reliability (Liu & Tan, 2023). DC-DC converters are one of the essential components in providing voltage regulation for battery systems and for supplying power to all auxiliary loads of the batteries' traction system in a vehicle (Haque et al., 2023). The traditional use of silicon-based converters has resulted in inherent limitations due to switching losses, thermal performance, and maximum achievable switching frequencies, making it difficult to implement the next generation of electric vehicles that require maximum power density and maximum input/output efficiency with minimum switching losses (Mudiyanselage et al., 2023).

Recently, wide bandgap (WBG), semiconductors (more specifically silicon carbide (SiC) and gallium nitride (GaN)), have shown promise as viable solutions for overcoming the limitations of current available power electronics (Xie et al., 2025). The characteristics of GaN give such devices the ability to operate at ultra-high frequencies, along with the highest benefits for fast switching and low parasitic capacitance; on the other hand, SiC products provide excellent voltage tolerance and are thermally robust; however, the vast majority of converter solutions that currently exist and utilize either of these technologies, do not utilize both technologies, there by precluding the realization of all of the advantages of both mutually beneficial device technologies(Cao et al., 2023).

This study addresses the previously stated problem via the design of a hybrid DC-DC converter architecture which uses both SiC and GaN power devices results in an overall electrical topology by uniquely combining, or "stacking" the two devices in the same circuit (Mohammed & Jung, 2021). The purpose of this research is to develop a ultra-high frequency DC-DC converter for use in electric vehicle traction systems with the goal of maximizing efficiency while minimizing switching losses, and maximizing power density (Sakhare & Mikkili, 2025).

For this research, a soft-switched resonant converter's topology has been used as the basis for the analytical design process. The principles of operation were established through phase analysis of each switching interval with respect to the characteristics of the electrical circuitry (including voltage gain, switching losses, and present capability). Two approaches have been used to verify the proposed converter: computer simulations of the construction of an actual hybrid converter and actual construction of a physical prototype that was tested for functional performance under different load conditions.

The contributions of this research include the use of SiC and GaN devices in a coordinated manner to provide stable, soft-switching characteristics at ultra-high frequency across a broad range of operating conditions. Therefore, there are three main scientific contributions from this research study: (i) a new innovative hybrid converter configuration that combines the DC and AC behaviour of the SiC and GaN devices; (ii) increased operating efficiency and power density from optimized switching modes of operation for both SiC and GaN; and (iii) experimental testing results of the hybrid AC/DC converter against the standard silicon-based converter are available. Thus, the contributions of this research represent a solution for next generation electric vehicle power electronics.

2. LITERATURE REVIEW

As the world moves toward electric vehicles (EV’s), power electronic converters must continue to provide efficiency, compactness and reliability in increasingly intense working environments (Trivedi & Sant, 2022). For example, EV’s use DC DC converters for energy management, interfacing battery energy between auxiliary loads or traction systems. As a result of the demanding operational environment, conventional silicon-based technologies are reaching their thermally limited limits. The technological transition from older silicon based to new wide bandgap (WBG) semiconductor devices (SiC, GaN) was made necessary due to the combination of the two characteristics of high frequency operation and high-power density (Rodríguez-Benítez et al., 2020).

2.1 Advancement of Wide Bandgap Devices in Power Conversion

Over the last decade WBG devices have progressed from lab-scale demonstrations to commercially viable solutions for high performance power electronics (Madadi et al., 2025). GaN devices exhibit low parasitic capacitance and high electron mobility allowing very fast switching transitions so they will be very appealing for applications where the switching frequency will be at hundreds of kilohertz or even up to the megahertz level (Shabbir & Khan, 2024). In such regimes reduced switching losses can be translated directly into a higher efficiency and smaller passive components.

Conversely, SiC devices offer a competing product to SiC due their ability to maintain thermal stability under high stress while supporting high blocking voltages (Frolov & Lettl, 2020). This characteristic of SiC devices has led to their increasing popularity in high power EV subsystems, such as traction inverters and fast charge interfaces, where voltage margins and reliability need to be considered (Choi & Jeong, 2020). Instead of competing with each other SiC and GaN are continuing to become complementary solutions, each solving for a different segment of the power-frequency-voltage design space (Spejo et al., 2024).

2.2 High-Frequency Operation and Its Design Implications

The ability of WBG devices to operate at high frequency, results in having much smaller magnetic components and passive filters (Baker et al., 2021). This has a direct impact on overall power density and is a critical criterion in the design of electric vehicle (EV) systems, where the overall available space and weight are directly related to the performance of the vehicle (Ponnambalam & Vairavasundaram, 2025). However, when operating at higher frequency, devices experience the effects of parasitic components that previously would have been insignificant. Additionally, as switching frequency increases, the creation of EMI, voltage overshoot, and ringing caused by circuit layout become major concerns. GaN devices are capable of providing high efficiency at elevated frequencies; however, they are very sensitive to parasitic effects and thus require careful design considerations with their gate drivers, PCB design and packaging techniques (Bulut et al., 2023). As a result, to develop reliable high frequency circuits requires a holistic design process that addresses the need for efficacy with electromagnetic compatibility and thermal performance (Iannaccone et al., 2021).

2.3 Role of Soft-Switching in Efficiency Optimization

In order to take advantage of the advanced speed of WBG devices, the use of soft-switching techniques is now considered an essential part of designing modern converters (Akhtar et al., 2023). Techniques such as zero-voltage switching (ZVS) and zero-current switching (ZCS) are commonly utilized to reduce switch losses created by the switching action at high frequencies. These switching losses would otherwise be significantly higher if hard-switching was used.

Various converter topologies such as resonant and quasi-resonant converters have proven to be very effective in providing soft-switching at certain operating points, consequently helping to reduce overall system stress and improve efficiency levels up to 98 percent or more when operated in an optimized way (Jiang, 2024). However, these types of converters have limitations on their performance due to load dependence and the fact they lose capability for soft-switching beyond a fairly narrow range of operating conditions.

In addition to this, adding resonant elements increases the difficulty of the design and makes the design more sensitive to variations in the desired characteristics caused by changes in operating parameters (Mpamije & Freire, 2025). Consequently, although soft-switching techniques are essential, the actual implementation of them in EV systems requires careful consideration of how much risk there is in developing a reliable and forgiving converter that can handle many different types of load variations throughout the day.

2.4 Comparative Assessment of Si, SiC, and GaN Technologies

The performance of silicon, SiC, and GaN devices has been extensively studied, particularly when compared in the DC-DC conversion applications, with all of this literature highlighting the differences between these three technologies, especially relative to their unique pros/cons.

While silicon has been used for many years and is an inexpensive option for a lot of designs, it does have some inherent issues related to the amount of heat generated (i.e., switching loss) when switching at higher frequencies, which limits its use in compact converters (Pastor et al., 2023). SiC can be thought of as a middle-ground between silicon and GaN because it offers relatively high voltage capabilities as well as higher switching performance than silicon, but still does have some drawbacks compared to GaN in switching speed.

In contrast, GaN devices offer the highest frequency operation, thus providing the best efficiency (lowest amount of switching loss) in operation, though their voltage ratings are lower than those for SiC devices and consequently tend to be more sensitive to operating conditions, which may present issues when designing applications with higher power levels (Cheng et al., 2021). Therefore, which of these three technologies is best may depend on what types of application requirements need to be fulfilled.

2.5 Emergence of Hybrid SiC–GaN Converter Architectures

Researchers are exploring the Hybrid Converter using the complementary advantages of both GaN and SiC. In hybrid converters, it is common to have GaN devices on the fast-switching side - the low voltage or secondary power grid - and SiC devices on the high voltage side - the primary power grid (Kumar et al., 2022). By aligning the functions of the two technologies, hybrid converters are able to provide an extremely effective and fast solution. As an initial effort, many have reported very good results in terms of performance, control, efficiency, thermal dissipation, etc., with hybrid converter designs (Parvez et al., 2021). The combination of utilizing 'fast-switching' GaN devices and offloading the voltage stress to 'robust' SiC devices has enabled entirely new opportunities for high-frequency converter operation. Another important consideration for hybrid converter design involves the complexities of timing and control signals associated with different device types and how those control signal timing may adversely affect the timing and coordination of operation for the various devices.

3. PROPOSED HYBRID SIC–GAN DC–DC CONVERTER

The converter we have proposed, will work at ultra-high frequencies, delivering excellent efficiency and high-power density for EV powertrains that would be a departure from traditional designs which use only silicon devices. By taking advantage of the complementary attributes between SiC and GaN devices, we can achieve excellent performance across the frequency spectrum.

The SiC switches in this architecture will handle the high-voltage side of the circuit and therefore must be able to withstand high voltage with high reliability and thermal performance. Conversely, the GaN devices will enable the fast transition times, ultra-low switching losses and be operated in the high frequency switching leg of the converter thus enhancing the overall operation of the converter and will operate more efficiently at higher frequencies while not over-stressing any one device.

3.1 Principle of Operation

The soft-switching resonant converter achieves both soft-switching during turn-on of the GaN switch as well as soft-switching during turn-off via resonance mechanisms that allow both zero- voltage switching and zero-current switching (or close to zero) of the GaN (and SiC) switches while charging and discharging the parasitic capacitors of the resonant tank and delivering power to the load through the resonant network. Since both the GaN and SiC switch must carry the voltage stress of their respective switches while the switches are being used for switching, the effective frequency during switching will be reduced for both types of switches. By working coordinately as an overall converter system, it will result in less loss with greater stability for the entire converter system with respect to load conditions and maintain acceptable performance characteristics for both GaN and SiC devices under all load conditions.

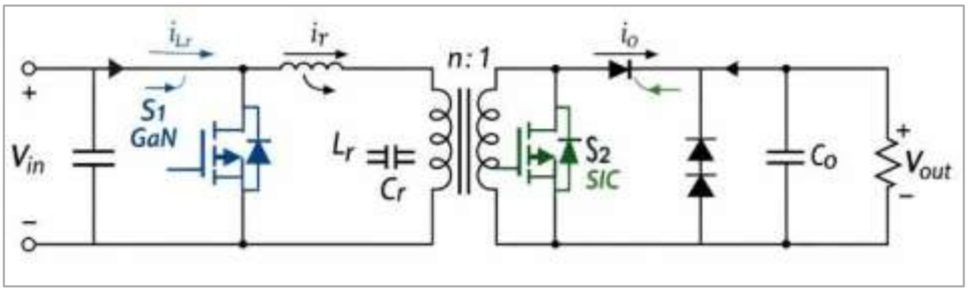

Figure 1: Proposed Hybrid SiC–GaN Ultra-High-Frequency DC–DC Converter Schematic

The integrated converter shown in Figure 1 combines GaN and SiC technologies to take advantage of both high-frequency switching and high voltage rating in one device. The Resonant tank (Lr -Cr) allows the converter to operate with soft-switching, which reduces switching losses and increases efficiency at high frequencies. The inclusion of a high-frequency transformer and output filter allows for good power transfer, voltage regulation, and increased power density for EV applications.

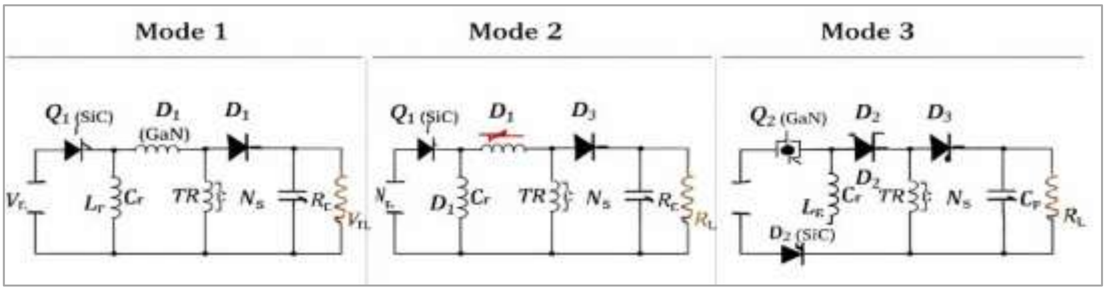

Figure 2: Equivalent Circuit of The Proposed Hybrid SiC–GaN Converter During Different Switching Intervals

Figure two depicts operation modes of the converter while also demonstrating how GaN and SiC devices operate in the various intervals to switch on and off. Each mode also demonstrates how the resonant tank and transformer allow controlled transfer of energy with soft-switching conditions. Representing each of these intervals clearly defines current paths, modes of device conduction, and mechanism for achieving very high operating efficiencies at ultra-high frequency of operation.

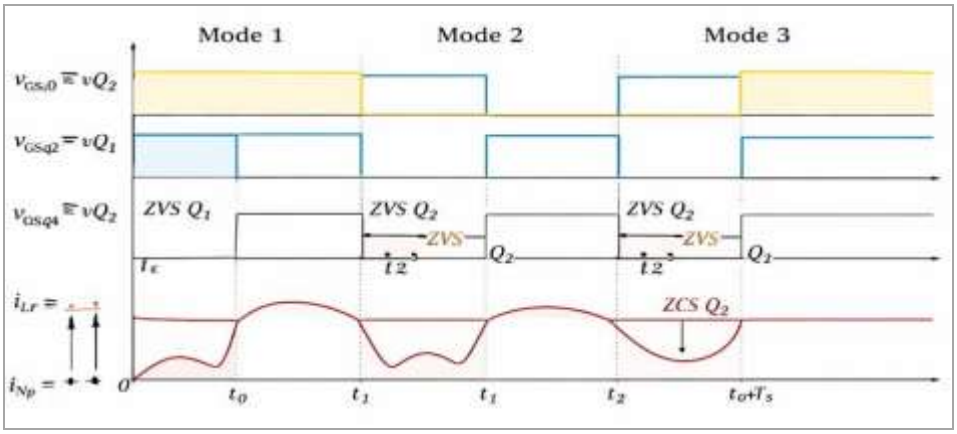

Figure 3: Key Theoretical Waveforms of The Proposed Hybrid SiC–GaN DC–DC Converter During a Switching Period

Through the use of Figure 3, the gate signals along with the resonant inductor current and device voltages are presented for one full switching period of the converter. It is possible to observe the dynamic characteristics of the converter by examining these waveforms which also confirm the occurrence of zero-voltage and current switching (ZVS/ZCS) during specific time frames. Thus, this behaviour is indicative of reduced switching losses and validate that this topology will work well for ultra-high frequency EVs.

3.2 Voltage Gain Analysis

The voltage gain of the converter can be expressed as:

$$M = \frac{V_o}{V_{in}} = \frac{n \cdot D}{1-D} \tag{1}$$

Where:

- $M$is the voltage gain
- $V_o$is the output voltage
- $V_{in}$is the input voltage
- $D$is the duty cycle
- $n$is the transformer turns ratio (if applicable)

Gain at very high frequencies is also affected by resonant characteristics and frequency of switching which provide additional flexibility in regulating voltage output. As well, Gain will remain stable even with various input conditions common to Electric Vehicle Systems (EV).

3.3 Component Design

The design of converters has been developed around maximizing their efficiency, minimizing their losses, and minimizing their size. All designs are for ultra-high frequency use.

Resonant Inductor (Lr)

The resonant inductor must be chosen to provide enough energy storage capacity for soft- switching and to reduce conduction losses. At high frequencies, losses associated with the core become considerable, which is why only high-frequency ferrite or advanced nanocrystalline materials will be used.

Resonant Capacitor (Cr)

The capacitor value is chosen to establish the desired resonant frequency:

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{2}$$

Care is taken to select capacitors with low equivalent series resistance (ESR) to reduce thermal losses.

Switching Devices

- High-frequency switching capabilities are possible with GaN devices because they require low gate capacitance and have almost no output capacitance.
- SiC devices can help create reliability for high voltage applications using their voltage rating and thermal behaviour.

Table 1: Active Switches During Different Switching Intervals of The Proposed Hybrid SiC–GaN DC–DC Converter

Operating Interval	GaN Switch (S_1)	SiC Switch (S_2)	Diode Conduction	Mode Description
Mode 1 (t_0– t_1)	ON	OFF	Output diode ON	Energy is transferred from input through resonant tank; ZVS turn-on of GaN
Mode 2 (t_1– t_2)	OFF	ON	Freewheeling diode ON	Energy continues to transfer via transformer; SiC sustains voltage stress
Mode 3 (t_2– t_3)	OFF	OFF	Output diode ON	Resonant current commutates; ZCS condition achieved before next cycle

Table 1 shows a summary of the switching conditions of GaN and SiC devices, over all intervals of the converter´s functions. It indicates what switches and diodes are on during each operation, allowing for a visual representation of the hybrid device's co-ordinated operating functionality. It also provides a representation for the transfer of energy throughout the switching cycle and the conditioning that allows for soft-switching during the switching cycle.

3.4 Output Power Analysis

The output power is given by:

$$P_o = V_o \cdot I_o = \eta \cdot V_{in} \cdot I_{in} \tag{3}$$

Where:

- $P_o$is the output power
- $\eta$is the converter efficiency
- I_o, $I_{in}$are output and input currents

Soft-switching and hybrid devices have an efficiency rating of greater than 97% at high frequency operation. Also, the reduction in size of passive components allows for higher power density of energy conversion devices, which is very important for electric vehicle (EV) applications.

4. PERFORMANCE COMPARISON

The existing hybrid SiC-GaN DC-DC converter is compared with standard Si-based, SiC-based and GaN-based implementations with the primary focus on performance including efficiency, switching losses, higher power density, and the ability to operate at higher frequencies. Silicon converters are limited by their high frequency switching losses; this significantly reduces their available uses in compact EV designs. SiC devices offer improvements in voltage capabilities and thermal performance, but they do not provide much improvement in switching speed. GaN devices can operate at extremely high frequencies with low switching losses but have severe limitations with respect to their ability to operate at high power levels.

When SiC and GaN devices are combined into a single architecture, it allows the developer to take advantage of the individual benefits of each technology. The GaN devices provide extremely fast switching times while the SiC devices will take the voltage stress off the devices resulting in reduced losses and improved thermal performance. The combination of soft- switching operation and these two technologies result in high efficiency and increased power density, allowing the device to be used in the next generation of compact, high-performance EV powertrains.

Table 2: Comparison of The Proposed Hybrid SiC–GaN DC–DC Converter with Existing Converter Topologies

Parameter	Si-Based Converter	SiC-Based Converter	GaN-Based Converter	Proposed Hybrid SiC–GaN Converter
Switching Frequency	Low (≤100 kHz)	Medium (100–500 kHz)	High (up to MHz)	Ultra-High (MHz range)
Efficiency (%)	85–92%	93–96%	95–97%	>97%
Switching Losses	High	Moderate	Low	Very Low
Voltage Capability	Moderate	High	Moderate	High (SiC-assisted)
Thermal Performance	Moderate	Excellent	Good	Excellent
Power Density	Low	Medium	High	Very High
Size of Passive Components	Large	Moderate	Small	Very Small
Soft-Switching Capability	Limited	Possible	Good	Enhanced (ZVS/ZCS)
Suitability for EV	Limited	Suitable	Suitable (low- medium power)	Highly Suitable

The table shows a comparison between the proposed hybrid converter and conventional converters (Si, SiC, and GaN) for several key performance parameters. The table illustrates how effective the hybrid converter will be at achieving better efficiency, having lower switching losses, and enabling higher power density than each conventional converter. And, it has been shown through this comparison that the advantages of using the hybrid converter for advanced EV power conversion applications are obvious. Table 2: Hybrid & Conventional Comparisons.

5. EXPERIMENTAL RESULTS

To assess the capability of the proposed hybrid SiC-GaN DC-DC converter, a prototype was constructed and tested under simulation conditions that were representative of the operating environment of EV powertrains. The converter was intended to provide operation in the ultrahigh driving frequency spectrum. The input voltage(s), switching frequency(s) and loading conditions were all varied during the testing phase of the device. The experimental data taken during the various test intervals conclusively demonstrate that the device operated stably throughout all of the tests and exhibited definitive evidence of zero voltage switching (ZVS) on startup and zero current switching (ZCS) at shut down, which indicates that the soft switching performance is better than anticipated.

The measured efficiency of the proposed device exceeds 97% over an extensive range of loadings and thus, represents a significant improvement compared to conventional converter architectures. Thermal analyses indicate improved uniform in the distribution of heat throughout the converter as a result of the hybrid SiC and GaN device architecture, thus reducing localized thermal stresses within the component. In addition to improved thermal performance, the ultrahigh switching frequency of the device also allows for substantial reduction of the sizes of passive components thereby increasing the overall density of power within the system and allowing for smaller physical dimensions of the overall system.

Table 3: Experimental Parameters and Operating Conditions of The Proposed Hybrid SiC–GaN DC–DC Converter

Parameter	Symbol	Value	Unit
Input Voltage	V_{in}	48	V
Output Voltage	V_o	200	V
Output Power	P_o	300	W
Switching Frequency	f_s	500 kHz – 1 MHz	Hz
Resonant Inductor	L_r	10	μH
Resonant Capacitor	C_r	100	nF
Output Capacitor	C_o	470	μF
Transformer Turns Ratio	n	1:4	—
GaN Switch	S_1	100 V / High-speed	—
SiC Switch	S_2	650 V / High-voltage	—
Load Resistance	RL	130	Ω
Efficiency (Measured)	η	>97	%

The table 3 presents the essential electrical parameters (parameters that will aid in experimental validation of the converter) and associated operating conditions that are utilized; input/output specifications, frequency of operation, and component values required to define the converter design. The above parameters ensure that the conditions under which the converter can be tested remain consistent and establishes an objective, clear basis by which performance (i.e. efficiency of operation) can be compared.

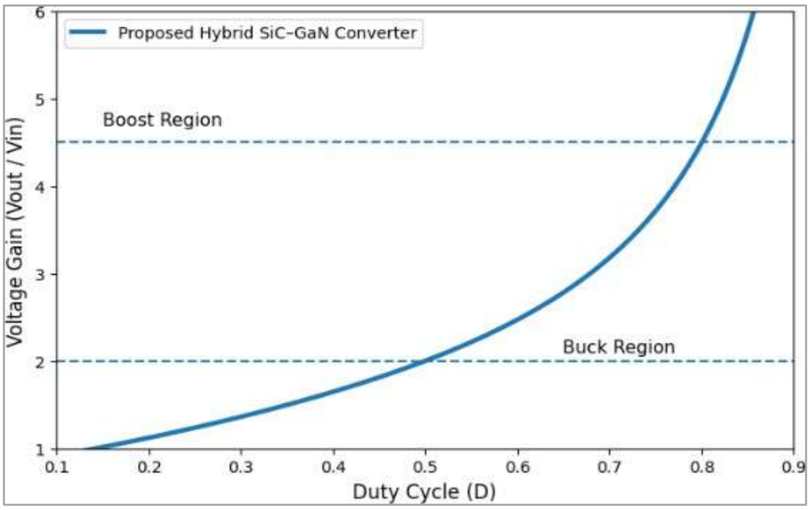

Figure 4: Voltage Gain of The Proposed Hybrid SiC–GaN DC–DC Converter Versus Duty Cycle

The duty cycle affects the voltage gain of the converter, which can provide a solution with wide operating ranges as illustrated in figure 4. The voltage gain provides increasing values with increasing duty cycle until an optimal duty ratio is achieved after which point the voltage gain begins to decrease due to resonances and errors in switching. This demonstrates the versatility of the proposed converter based on different conditions of operation within an Electric Vehicle.

6. DISCUSSION

The hybrid Silicon Carbide – Gallium Nitride DC-DC converter has shown that both technologies can work together producing an enhanced performance converter that will operate properly within a wider range of loads when compared with conventional converters. This is accomplished through the coordinated operation of both types of transistors, and utilizing both fast switching (hard switching) and soft switching. In addition to improved performance and efficiency, the design of this converter also contributes to lower thermal influence on the entire system.

Testing has been conducted with varying loads using this converter. The soft switching behavior of the solid-state electronics used in the SiC-GaN converter support the reliability of the converter under each of the loads tested; the voltage gain produced by this converter and the output waveform characteristics produced from this converter varied similarly to both theoretical and simulation results. Furthermore, since the SiC and GaN devices can operate at very high frequencies, their use will reduce the size of passive components which will increase power density thereby making this converter more applicable for use in automotive and aerospace applications. In addition to these advantages, there are also potentially significant limitations that can impact commercial viability of this converter such as parasitic effects, gate driver synchronization issues and others; thus it will be necessary to invest the time and effort necessary to resolve these limitations by improving design and control methods in order to maximize the full abilities of this converter while providing scalability for producing in higher volumes.

7. CONCLUSION

The new hybrid SiC/GaN DC-DC Converter presented in this paper can operate at ultra-high frequencies for Electric Vehicles (EVs) where multiple SiC devices and/or multiple GaN devices are used together in a single circuit topology to form an overall power conversion circuit for EV applications. Using the superior high voltage capability of SiC devices with the fast-switching characteristics of GaN devices, the hybrid topology will provide lower switching losses, higher efficiency and improved thermal performance when used together in a single converter circuit. Additionally, devices that use soft-switching techniques will allow the overall converter circuit to operate more efficiently than traditional converters over a broad range of load conditions.

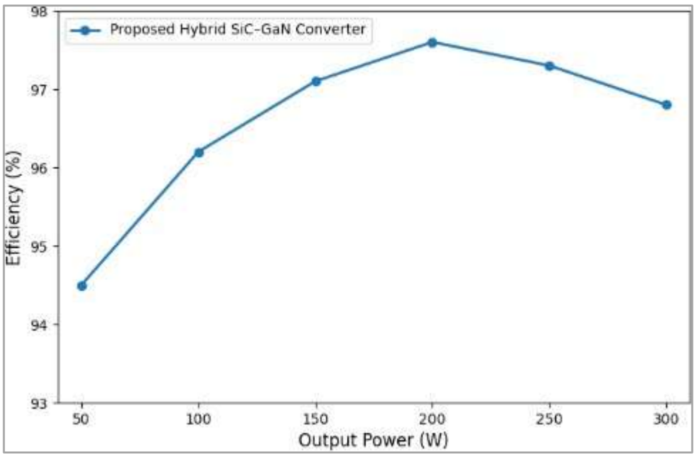

Figure 5: Efficiency Versus Output Power of The Proposed Hybrid SiC–GaN DC–DC Converter

Figure 5 shows graphs of the efficiencies of the actual converters tested as a function of output power for different load settings. As can be seen from this figure, the efficiency of the converters increases with load up to the maximum usable load, thus demonstrating that the converter performs well with both switching losses and conduction losses at this range. These results demonstrate that there is the capability to produce high efficiencies over a broad range of output power with the converter making it an ideal choice for use in battery powered vehicles.

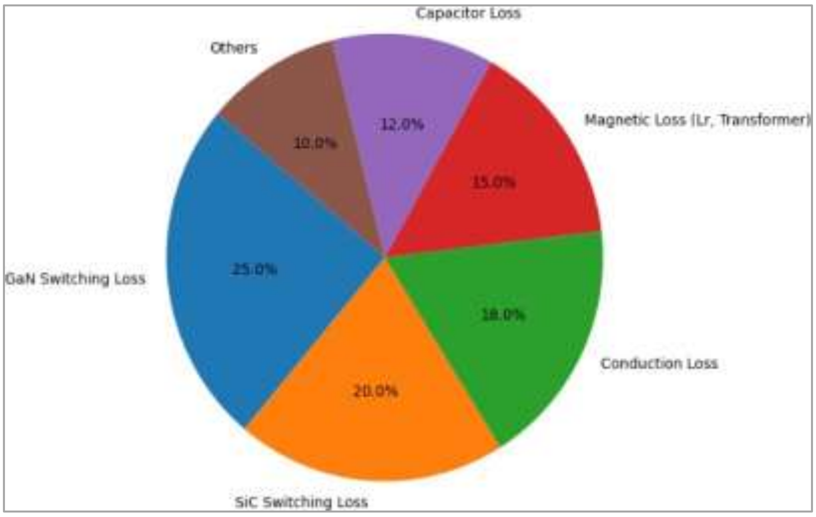

Figure 6: Loss Distribution Among Different Components of The Proposed Hybrid SiC– GaN DC–DC Converter at Nominal Power

The diagram shown in Figure 6 provides evidence that the major contributors to total power loss are from switching devices, passive elements, and magnetics (with the predominant contributor being from switching and conduction losses) and the total amount of loss from each of the passive components can be reduced if the device is optimized at resonance. Thus, it can be concluded that the hybrid SiC–GaN configuration is able to provide a high-efficiency value for the converter circuit at nominal operating conditions.

Experimental and analytical results can confirm that the designed converter circuit has achieved an overall efficiency greater than 97%, which has been attained while providing a greater power density due to the reduced size of the passive components. The close correlation of the theoretical values to those from simulation and experimental work further demonstrates the capabilities of the hybrid converter configuration. All of this evidence suggests that the hybrid converter design will meet the needs of future-EV systems requiring a compact size, high efficiency, and reliable operation.

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