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MODEL-BASED DESIGN AND THERMAL-ELECTRICAL CO-SIMULATION OF A BIDIRECTIONAL ONBOARD CHARGER FOR ELECTRIFIED VEHICLES USING GAN AND SIC TECHNOLOGIES

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ABSTRACT

Using silicon (Si), silicon carbide (SiC), and gallium nitride (GaN) switching devices, this article compares three isolation converters based on the Dual Active Bridge (DAB) architecture for a level-2 integrated onboard charger (OBC). Design trade-offs, operational limitations, and performance indicators including specific power, power density, and efficiency are all assessed in the research. Despite operating at a 2.5-fold greater switching frequency, experimental findings show that both SiC and GaN converters function better than their Si-based counterparts, delivering higher efficiency. The most notable benefits were shown by the GaN-based converter, which showed a 500% increase in specific power, a 79% weight reduction, and a 53% volume decrease. The advantages of wide-bandgap materials in OBC applications are further shown by system efficiency comparisons. These results highlight how GaN and SiC technologies might improve power electronics for EV charging systems, allowing for smaller, lighter, and more effective designs.

Keywords: Vehicles, Converter, Silicon, Function, Power Density.

I. INTRODUCTION

Developments in power electronics are essential for enhancing the effectiveness, power density, and general performance of onboard chargers (OBCs) as the market for electric vehicles (EVs) keeps expanding. Because of its high efficiency, capacity to manage numerous energy sources, and ability to transmit energy in both directions, the Dual Active Bridge (DAB) three-port architecture has become a viable option for OBCs. Nonetheless, the performance of these converters is greatly impacted by the semiconductor materials used for the power switching devices. The most often utilized materials among the alternatives are silicon (Si), silicon carbide (SiC), and gallium nitride (GaN), each of which has unique benefits and drawbacks.

The power electronics sector has long been dominated by silicon-based power devices because of their proven production methods and affordability. They are less appropriate for high-power-density applications, nevertheless, because to their greater switching losses and reduced efficiency. SiC and GaN are examples of wide-bandgap (WBG) semiconductors that have become better substitutes because to their increased switching frequencies, reduced losses, and enhanced thermal performance. These benefits enable the creation of converters that are more efficient and small, which makes them perfect for EV applications. Three isolation converters using Si, SiC, and GaN semiconductor technologies are compared in this research. All three are based on the DAB topology. The goal is to showcase the advantages of WBG materials in OBC applications while analyzing the design trade-offs, operational limitations, and performance metrics of each converter.

To guarantee a fair comparison, the three isolation converters were constructed and tested in controlled experimental settings. While the SiC and GaN-based converters used WBG semiconductor devices, the Si-based isolation converter was constructed using traditional silicon MOSFETs. With special focus on switching frequency, thermal management, and device packaging, the designs were improved for efficiency and power density. A resistive load bank was used to test the converters at different switching frequencies in order to assess performance. In order to directly evaluate the ways in which each material affects efficiency and power conversion characteristics, the Si-based converter ran at 40 kHz while the SiC and GaN converters were evaluated at 100 kHz.

According to experimental data, both SiC and GaN converters performed better than their Si-based counterparts, obtaining higher efficiency even though they had to operate at a switching frequency that was 2.5 times higher. Comparing the isolation converters' efficiencies revealed that the Si-based converter had a little lower peak efficiency of 98.4%, while the GaN and SiC-based converters performed similarly, both of which had peak efficiency levels of 99.0%. But when it came to weight and volume reduction, the benefits of GaN technology were more obvious. The GaN-based converter obtained a 500% gain in specific power, a 170% increase in power density, a 79% decrease in weight, and a 53% reduction in volume when compared to the Si-based isolation converter. With a 24% volume reduction, a 28% weight reduction, a 72% power density gain, and an 82% specific power increase, the SiC-based converter likewise showed significant advances, although to a lower degree.

The SiC and GaN isolation converters were tested as integrated OBCs by integrating them with a 100 kW segmented inverter in order to further evaluate their practicality. Six 1200 V, 120 A twin-pack SiC MOSFET modules made up the segmented inverter, which was constructed with reconfigurable parts for flexible testing as a dual three-phase or segmented three-phase inverter. The system's performance was assessed under practical operating settings using a 14.92 kW induction motor as a traction motor. The identical induction motor and a 55 kW segmented inverter based on IGBT were used to evaluate the Si-based isolation converter for comparison.

The benefits of WBG-based converters were further supported by system efficiency comparisons for the integrated OBCs. The efficiency of the SiC and GaN converters was consistently better than that of the Si-based equivalent, even though they operated at a higher switching frequency. Because of their reduced conduction and switching losses, which enable more effective power conversion, WBG materials perform better than other materials. Furthermore, switching at higher frequencies results in smaller passive components, which significantly lowers weight and volume.

The advantages of WBG semiconductor devices in OBC applications are highlighted by the study's findings. More compact, lightweight, and efficient designs are made possible by the use of SiC and GaN in isolation converters, which makes them ideal for EV applications where weight and space are crucial factors. The most notable improvements in weight and volume reduction among the three technologies are provided by GaN-based converters, indicating its potential as a very attractive option for next-generation EV charging systems. Although SiC-based converters outperform their Si-based counterparts by a significant margin, the advantages of GaN-based devices are more noticeable.

The advantages of SiC and GaN isolation converters over conventional Si-based converters for level-2 integrated OBCs is highlighted in this comparative research. The experimental findings unequivocally show that WBG materials provide significant benefits in terms of system integration, power density, and efficiency. Particularly noteworthy for its remarkable power density and targeted power enhancements is the GaN-based converter. To hasten the broad use of WBG-based power electronics in EV applications, future studies might investigate more sophisticated thermal management plans and cost-cutting measures.

II. REVIEW OF LITERATURE

Wouters, Hans & Martinez, Wilmar. (2023) Electric cars, or EVs, are essential to the shift to a carbon-neutral and sustainable future. However, the ease of charging EVs and the accessibility of their infrastructure are presently prerequisites for their broad acceptance. As a result, on-board chargers (OBCs), which provide an AC charging option integrated into the majority of electric cars, have drawn a lot of interest. Moreover, reverse power flow is made possible by bidirectional OBCs, allowing the EV battery to power other appliances, houses, or even the electrical grid. But as the trend toward bidirectional OBCs becomes more apparent, new design problems for power converters emerge, making the need for small, cost-effective, and high-efficiency solutions even more pressing. Through an analysis of more than 500 papers, this study provides a thorough evaluation of the state-of-the-art bidirectional on-board chargers, highlighting the major trends, obstacles, and areas for future research that will affect the creation of next-generation bidirectional OBCs. As a result, several tactics are used to get state-of-the-art performance. In order to increase efficiency and power density, this involves the development of high-voltage batteries, powertrain integration, the expanding usage of wide-bandgap semiconductors, and the use of integrated planar magnetic components. A CSV file including all relevant references is included with this publication to aid in statistical analysis, future study, and other contributions.

Dini, Pierpaolo & Saponara, Sergio. (2021) The design of a bidirectional onboard charger (OBC) device for contemporary hybrid and fully electric cars is suggested in this research using a model-based methodology. Since simulating such precise models is computationally costly, it is not possible to integrate it into the same virtual environment used to solve the circuit equations. This limits the thoroughness of the study during the design phase and necessitates lengthy wait periods. It also implies that thermal and electrical models do not communicate with one another. The design of a modular bidirectional single-phase OBC, which consists of a Dual Active Bridge (DAB) type DC/DC converter after a Totem Pole-type AC/DC converter with Power Factor Correction (PFC), is used as a case study. To get optimal performance and efficiency, we specifically look at a 7 kW OBC, whose modules are made up of switching devices manufactured using contemporary 900 V GaN (Gallium Nitrade) and 1200 V SiC (Silicon Carbide) technology. In order to conduct validation using as realistic simulations as feasible, we provide a method for sizing and choosing electrical equipment based on the behavior study using circuit models of the Totem Pole PFC and DAB converter. The robustness of the implemented control algorithms under different operating situations is validated by testing the produced models across a range of realistic operating scenarios. A thorough robustness study of the parametric modifications of the model with regard to the nominal case further strengthens the validation of the models and control loops. Every simulation that was produced adhered to the operational parameters of the chosen components and devices, whose electrical and thermal behavior is described in data sheets.

Yuan, Jiaqi et al., (2021) There are many chances to further use renewable energy in the automobile industry thanks to the rapid growth of electric cars (EVs). Due to their affordability and ease of installation, on-board chargers, or OBCs, are often seen in EVs. An OBC must be very efficient and power-dense because to the vehicle's limited size and short charging time. Furthermore, the automobile industry is becoming more interested in bidirectional power flow solutions due to the potential for EVs to provide electricity back into the grid. The state-of-the-art bidirectional OBC solutions are thoroughly reviewed and investigated in this work. It examines the state of affairs at the moment, including key components, smart operating modes, industry standards, architectures and configurations, and commercially available goods. Two-stage and single-stage architectures are among the potential topologies for bidirectional OBCs that are thoroughly reviewed. This study also discusses future trends and problems for wireless charging systems, wide bandgap technology, thermal management, system integration, and topologies.

Da Silva, Carlos et al., (2020) To maximize the charging speed, dependability, safety, and affordability of today's conservatively constructed electric car charging systems, significant advancements are required. To ensure dependable continuous operation, scalability, and minimal footprint, these innovative engineering systems must be designed and optimized while simultaneously taking into account thermal and electrical phenomena, as well as component- and system-level dynamics and control. In a high-density, on-board, bi-directional charger with vehicle-to-grid (V2G), grid-to-vehicle (G2V), vehicle-to-house (V2H), and vehicle-to-vehicle (V2V) power transfer capabilities, this study tackles the simultaneous thermal and electrical design restrictions. This charger's electrical architecture is made up of series-connected dc-dc and dc-ac power stages. A printed circuit board (PCB) containing 16 surface-mount silicon carbide MOSFETs, three inductors, and a transformer is used to create the power-stage circuits. This work's primary objective is to examine how the cooling architecture and PCB layout interact, and how this affects parasitic inductance and heat dissipation. The performance of three generations of this multifunctional charger using various design approaches is compared in this paper, which also suggests high-level design principles based on multi-physics simulations and experimental testing.

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III. PROPOSED METHODOLOGY

This study compares three isolation converter designs for a level-2 integrated onboard charger that use Si, SiC, and GaN switching devices, respectively, and are all based on the DAB three-port topology. Operational limitations and design trade-offs are examined, along with performance indicators like power density and efficiency and comparing experimental findings.

IV. EXPERIMENTAL RESULTS

A resistive load bank was used to test the isolation converters at various switching frequencies. Figure 1 compares output power and efficiency. Despite switching at a frequency that is 2.5 times greater than the Si-based equivalent, the SiC and GaN converters have comparable efficiency but higher numbers.

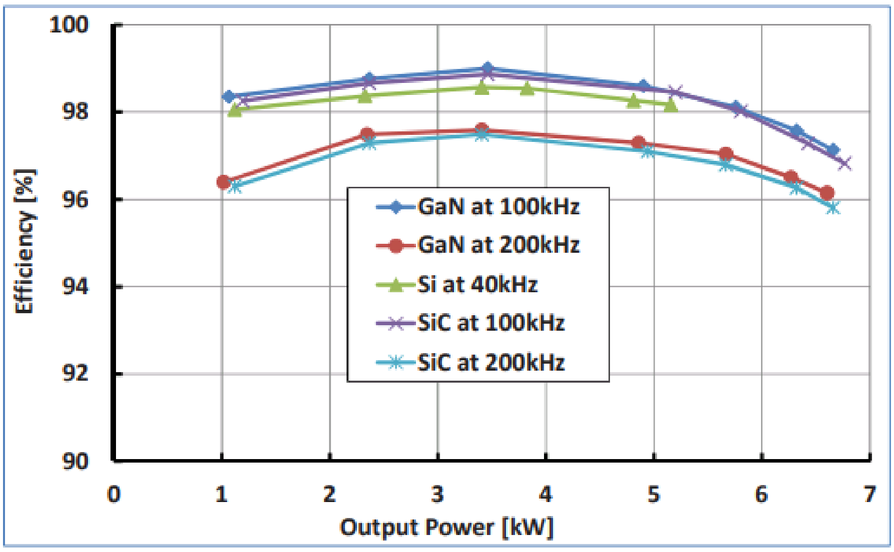

Figure 1 Efficiency comparison of the Si, SiC, and GaN isolation converters.

A comparison of the three converters' weight, volume, and peak efficiency is shown in Table 1. The GaN-based isolation converter obtained a 500% gain in specific power, a 170% increase in power density, a 79% decrease in weight, and a 53% reduction in volume when compared to the Si-based converter. The SiC converter figures are 24%, 28%, 72%, and 82%, in that order. The GaN converter's device and converter packaging has made a substantial contribution to the weight and volume reduction.

Table 1 Comparison of Si, Sic and Gan Based Isolation Converters

	Si isolation converter	SiC isolation converter	GaN isolation converter
Power (kW)	5.2	6.8	6.6

Volume (L)	1.34	1.02	0.63
Mass (kg)	3.27	2.35	0.69
Power density (kW/L)	3.9	6.7	10.5
Specific power (kW/kg)	1.6	2.9	9.6
Peak efficiency (%)	98.4 (40 kHz)	99.0 (100 kHz)	99.0 (100 kHz)

To evaluate the SiC and GaN isolation converters' performance as integrated OBCs, they were connected to a 100 kW segmented inverter. Six dual-pack SiC MOSFET modules with a voltage of 1200 V and 120 A were used to construct the segmented inverter. The inverter was readily reconfigurable as a segmented three-phase inverter or a dual three-phase inverter by using 3-D-printed components. Furthermore, a 14.92 kW, 230 Vrms, 45.4 Arms induction motor was used as a traction motor throughout the experiments. The motor is a good fit for the segmented inverter since it has two sets of stator windings with all leads accessible.

The identical motor and a 55 kW IGBT segmented inverter were used to test the Si isolation converter. Figure 2 compares the output power at a 240 V input ac source to the system efficiency of the integrated OBCs with the Si, SiC, or GaN isolation converter. Once again, despite switching at a 2.5-fold greater frequency, the SiC and GaN converter-based OBCs had comparable efficiency but higher numbers than their Si-based cousin.

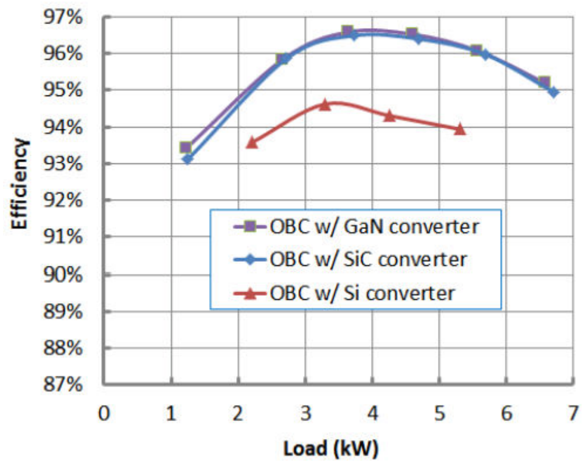

Figure 2 System efficiency comparison of integrated OBCs with the Si, SiC, or GaN isolation converter.

V. CONCLUSION

The substantial benefits of wide-bandgap (WBG) semiconductor materials over traditional silicon-based devices are demonstrated by the comparison of isolation converters based on Si, SiC, and GaN for a level-2 integrated onboard charger (OBC). Despite operating at a 2.5-fold higher switching frequency, the experimental findings show that both SiC and GaN converters outperform their Si-based counterparts in terms of efficiency. This improvement is ascribed to WBG materials' lower conduction and switching losses, which enable more effective power conversion and less need for thermal management. The GaN-based converter demonstrated the most notable improvements among the three technologies, achieving notable weight and volume reductions as well as notable increases in specific power and power density. Although the SiC-based converter outperformed the Si-based design in terms of compactness and power density, it fell short of the GaN-based converter. According to these results, GaN technology is the most viable avenue for creating OBCs for electric cars that are tiny, lightweight, and high-performing. The study's overall findings highlight SiC and GaN's potential to transform power electronics for EV applications. To enable the broader use of these cutting-edge semiconductor materials in commercial OBC designs, future research should concentrate on improving thermal management and cost-cutting techniques.

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