Transformative Innovations:

Bidirectional CLLC Resonant Converters and Advanced Materials in Power Electronics for Military Vehicles

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Advanced technologies are crucial for achieving tactical superiority and operational efficiency in modern warfare. Power electronics play a key role in propelling military vehicles forward, with bidirectional CLLC resonant converters emerging as a transformative innovation. These converters seamlessly manage bidirectional power flow, meeting the intricate energy needs of military vehicles. They convert and transfer energy between sources and loads, extending mission durations, reducing logistical constraints, and enhancing adaptability in demanding operational environments.

This exploration delves into the transformative potential of bidirectional CLLC resonant converters, spotlighting their role in revolutionizing power electronics for military vehicles and underscoring their indispensable contribution to shaping the contemporary battlefield. The term CLLC stands for "Capacitor-Inductor-Inductor-Capacitor," a commonly used resonant circuit configuration that involves arranging two inductors and two capacitors in a series-parallel layout. This circuit harnesses the inherent characteristics of these components for efficient energy transfer and voltage regulation across various electronic systems. By combining capacitors and inductors into a resonant tank circuit, energy flow is effectively managed while reducing switching losses.

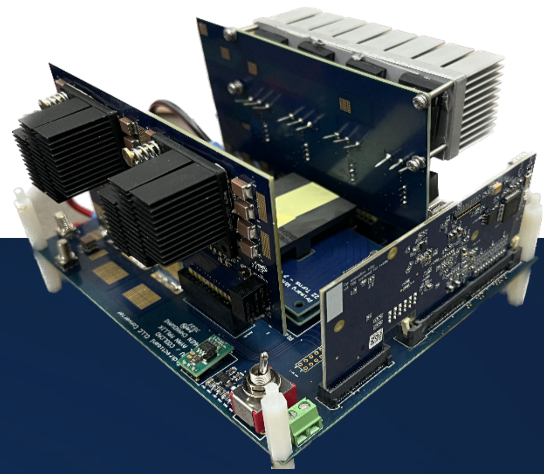

Figure 1. Hardware prototype of the newly developed 2.5kW nominal power, 3.3kW peak power CLLC converter.

The Bidirectional CLLC Resonant Converter is a sophisticated power electronics structure designed for efficient energy conversion in contexts requiring bidirectional power flow. This converter strategically utilizes the CLLC resonant circuit design, characterized by a series-parallel arrangement of two inductors and two capacitors. By incorporating resonant components, the converter minimizes switching losses and improves overall efficiency for all loading conditions. Its bidirectional capability allows for seamless energy exchange between sources and loads, eliminating the need for additional components. With compact dimensions, high power quality, and enhanced control adaptability, it is a versatile solution for contemporary energy management needs.

Silicon Carbide (SiC) Components in Power Electronic

Silicon Carbide (SiC) is a hard, covalently bonded material that consists of one silicon (Si) atom and four carbon (C) atoms. It is a non-oxide ceramic material. It is one of the most important advanced ceramic materials in use today. GaN, or Gallium Nitride, is a binary compound formed by combining gallium (Ga) and nitrogen (N). It is a direct bandgap semiconductor material that has become increasingly important in the field of electronics and optoelectronics. The integration of advanced materials like Silicon Carbide (SiC) and

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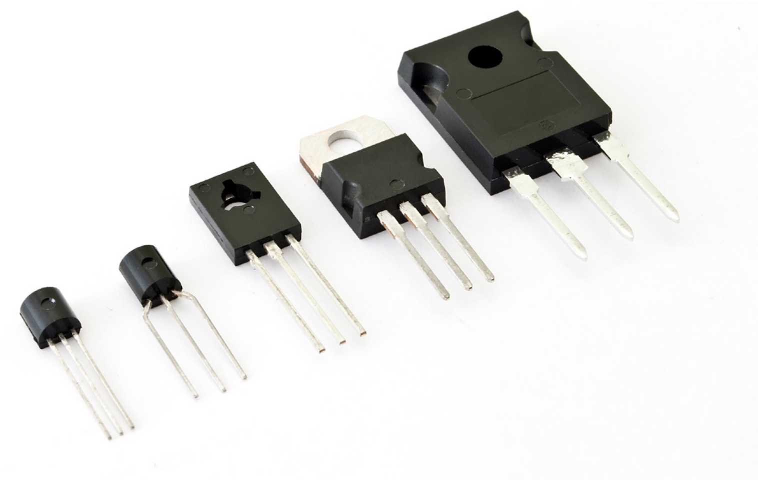
Gallium Nitride (GaN) components within power electronics, particularly in power converters and inverters, has inaugurated a transformative era of heightened performance and efficiency. SiC and GaN, both surpassing traditional silicon in material properties, offer a plethora of advantages that are reshaping power electronics applications. Silicon Carbide (SiC) components have introduced a new era of performance and efficiency in power electronics. SiC components operate well at high temperatures, maintain performance in demanding conditions, and offer superior breakdown voltage capabilities, contributing to reduced losses, increased power density, and more streamlined designs. Gallium Nitride (GaN) devices, known for high electron mobility, enable faster-switching speeds, reducing switching losses and improving system efficiency. Incorporating SiC and GaN components in power converters and inverters results in decreased energy wastage, better power quality, and enhanced system reliability.

Electromagnetic Interference (EMI) in Power Electronics

EMI (Electromagnetic Interference) filtering is essential in high-frequency switching technologies like Bidirectional CLLC resonant converters, which are characterized by rapid voltage and current transitions, leading to substantial electromagnetic noise. Filtering mitigates unwanted electromagnetic noise, preventing interference with nearby components, communication signals, and sensitive equipment. Effective EMI filtering strategies ensure regulatory compliance, system reliability, and signal integrity, safeguarding the efficiency and stability of bidirectional CLLC resonant converters in modern power electronics.



CoolCAD Electronics Has the Solution

CoolCAD Electronics is at the forefront of innovation with its Silicon Carbide (SiC) technology, especially in bidirectional CLLC resonant converters. By leveraging SiC's extraordinary properties, CoolCAD is transforming energy conversion efficiency and performance in high-power electronics. Addressing the crucial issue of Electromagnetic Interference (EMI) filtering, CoolCAD effectively mitigates disruptive electromagnetic noise in bidirectional CLLC resonant converters, ensuring smooth operation and preventing interference with nearby components and communication signals. Combining SiC technology with robust EMI filtering, CoolCAD offers efficient, reliable, and EMI-controlled solutions for various industries, including renewable energy and electric vehicles.

CoolCAD's pioneering development of SiC power devices includes 650V and 1200V SiC power MOSFETs that outperform conventional silicon devices in power, efficiency, and portability. With a range of breakdown voltages and current ratings, these power MOSFETs offer exceptionally low on-resistance (Ron) and minimal leakage in the blocking state. CoolCAD's proprietary fabrication process, based on high-quality SiC epitaxial layers and meticulous annealing, ensures a superior SiC-SiO2 gate oxide dielectric layer. The expertly tuned doping profile, device design, and edge termination contribute to remarkably low Ron and impressive breakdown voltage.

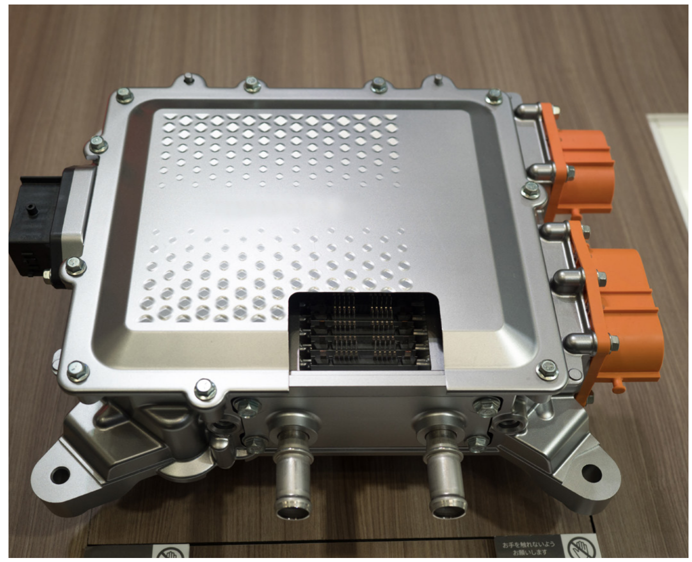
CoolCAD has been awarded 21 Phase I SBIRs (Small Business Innovation Research grants), 8 Phase II SBIRs, and several beyond Phase II awards matched by investors and contracts. Additionally, CoolCAD has been chosen for many service and R&D contracts awarded by other private companies. In 2021, CoolCAD was awarded a multi-year contract from DARPA (Defense Advanced Research Projects Agency) to develop high-temperature electronics.

Importance of Low on-resistance (Ron)

Low Ron and high breakdown voltage are vital for efficiency, reliability, and overall performance in power electronics. Low Ron reduces conduction losses, enabling efficient energy transfer and minimizing heat generation, essential for applications like power converters. High breakdown voltage ensures device integrity, protecting against voltage spikes and transients without failure.

The combination of low Ron and high breakdown voltage enhances energy efficiency and extends device lifespan, contributing to stable and resilient systems in industries like renewable energy, electric vehicles, and industrial automation.

The quality of the oxide dielectric layer is crucial for SiC devices' performance. As a gate insulator, this layer controls device switching and conduction. A high-quality oxide layer maintains low gate leakage current and robust device operation, particularly in high-voltage and high-power applications. A well-engineered oxide layer enhances voltage stress resistance, prevents premature breakdown, and ensures long-term reliability. Optimizing the oxide dielectric layer contributes to low Ron and low CISS by maximizing channel resistance and minimizing gate-source capacitance, impacting switching speed and efficiency. SiC's unique material properties enable high-quality oxide dielectric layers, unlocking SiC devices' potential across various industries where performance and reliability are paramount.



CoolCAD Electronics specializes in high-performance Silicon Carbide (SiC) devices, whose performance hinges on the quality of the oxide dielectric layer. This layer is crucial for device switching and conduction, especially in high-voltage and high-power applications like the bidirectional CLLC converters used in military vehicles. A well-engineered oxide layer minimizes gate leakage current and enhances resilience against high electric fields and voltage stress, ensuring robust operation and long-term reliability. Moreover, refining the oxide layer reduces on-resistance by increasing channel mobility, impacting switching speed and efficiency. This is vital across applications including power converters, switching power supplies, electric vehicles, renewable energy power converters, and advanced military ground vehicles.

CoolCAD's innovative multi-kW CLLC DC-DC converter, with a resonant frequency of 500kHz, focuses on power density, utilizing a high-frequency planar transformer (HFPT) with integrated leakage features, along with cutting-edge SiC and Gallium Nitride (GaN) power semiconductor devices. Designed for a 2.5kW load and nominal voltage conversion of 600V-28V, the prototype achieves milestones like optimized HFPT design for reduced winding losses, Zero Voltage Switching (ZVS) for primary and secondary switches, Synchronous Rectification (SR) switching for enhanced efficiency, remarkable operational efficiency (97.35% forward and 95.93% reverse), and compliance with MIL-STD-461G and MIL-PRF-GCS600A/MIL-STD-1275D standards. The proof-of-concept converter has a volume of 1.78 liters, a nominal power of 2.5kW, a power density of 1.404 kW/L, and a weight of 1.1kg, resulting in a gravimetric power density of 2.272 kW/kg.

A higher density 15kW converter based on a modular design is in development, featuring smaller orthogonal connectors, vertical placement of HFPT with closely spaced bridges, elimination of PWM connection points, and adoption of higher current devices on the primary side. These modifications aim to reduce converter volume to 1.035L, increase rated power to 3.3kW per module, and achieve a power density of 3.188kW/L and gravimetric power density of 3kW/kg.

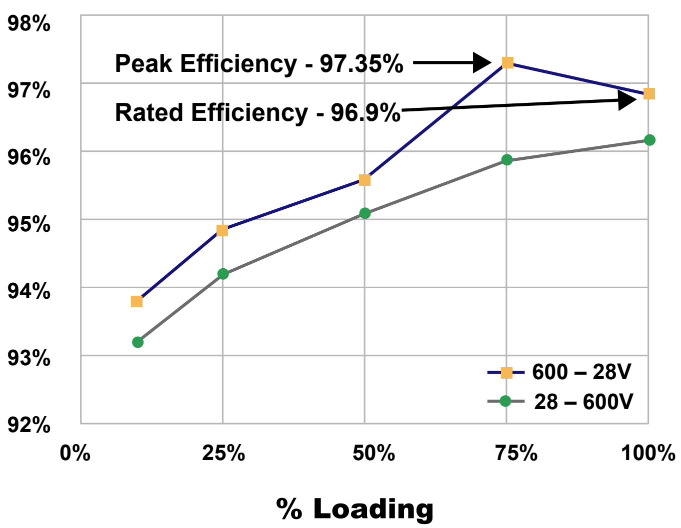


Figure 2. Efficiency v/s. load trend of the developed converter.

Summary

In the landscape of modern warfare, the integration of cutting-edge technologies is a linchpin for achieving tactical supremacy and operational efficiency. Power electronics, anchored by bidirectional CLLC resonant converters, are revolutionizing energy management in modern warfare, particularly in military vehicles. These converters manage bidirectional power flow, optimizing energy distribution and extending mission durations while reducing logistical challenges and increasing adaptability in dynamic battlefields. Silicon Carbide (SiC) and Gallium Nitride (GaN) components are key to this transformation, offering superior performance and efficiency compared to conventional silicon. SiC excels in high temperatures and reduces losses, optimizing power converters, while GaN's fast switching speeds reduce losses and boost efficiency. These advances, powered by SiC and GaN, are reshaping industries from renewable energy and electric vehicles to military operations.

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