DEVELOPMENT OF A 90kW, TWO-PHASE, BI-DIRECTIONAL DC-DC CONVERTER FOR POWER DENSE APPLICATIONS

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ABSTRACT

In this summary, the preliminary design and test results of a two-phase interleaved, non-isolated, bi-directional DC-DC converter (BDC) for hybrid electric vehicle applications are presented. The converter was initially designed for sustained operation at 90kW, providing power flow in either direction between the low-voltage vehicle battery pack (nominal 320V) and its high-voltage load bus (nominal 600V). Strong design emphasis was placed on high power density, and high temperature operation. Initial goals for these criteria were 8.3 kW/liter and 80ºC liquid coolant temperature, respectively. Tests using commercially available components, with less than optimal heat sinking and 25ºC coolant resulted in maximum output power levels of 50kW in both buck and boost modes at an estimated power density of 2.7 kW/liter. Improvements in future design modifications are discussed.

1. INTRODUCTION

The development of advanced electric power conversion systems is essential to the Army's strategic plan to transform its field operations into a more dynamically responsive force. As a key initiative in the Future Combat Systems (FCS) program, power converters are being designed to meet the needs of an evolving family of manned and unmanned weapons systems. One focus in this initiative is the development of compact and light-weight power electronics systems for hybrid-electric vehicle propulsion and pulsed power loads. The Army Research Laboratory (ARL) and Virginia Polytechnic Institute and State University (VPI) recently collaborated in the development of a bi-directional DC-DC converter (BDC) in support of the FCS program. In this presentation, we discuss a bi-directional converter in light of FCS goals, respective limitations of present electronics technology, and research thrusts that are being pursued to address technology shortfalls.

2. CONVERTER DESIGN

The goals of the effort were to design and build a high power density, high temperature, 90kW continuous power, BDC prototype to fulfill the power system requirements of an FCS vehicle. As shown in Figure 1, the BDC's role is to transfer power between the battery pack (nominal 320 V) and the propulsion power bus (nominal 600V).

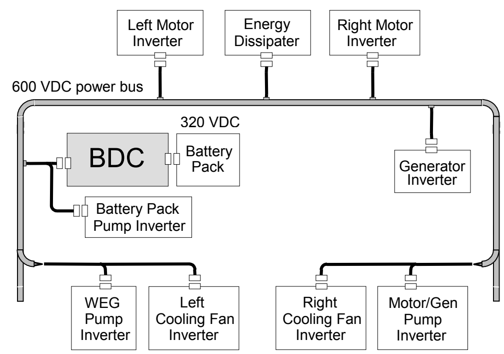

Fig. 1. Notional FCS hybrid electric power bus and the bi-directional DC-DC converter.

Using commercially available components, the system was designed for a low-side (battery pack) voltage range of 320-580V and a high-side (power bus) voltage range of 580-630V. With high power density being the leading converter design criterion, compact components and system integration were essential. The range of voltage conversion ratios favored a power dense design through the implementation of a non-isolated topology, which required fewer active devices and allowed smaller and less complex magnetic components to be used. As a result, the selected topology served as a basic building block facilitating the construction of a scalable converter using multiple blocks as phases. In this application, two phases were implemented. The scaling approach offered additional benefits at the system level by allowing a wider range of available and more optimal components to be applied for more flexibility in system design for a targeted power level. More importantly, multi-phase systems can be interleaved by introducing time domain phase shifts. This technique was used to drastically reduce high- and low-side ripple voltages and allow physically smaller input and output capacitors to be used to meet ripple specifications. Simulation results for the two-phase interleaved buck-mode converter show an output voltage ripple reduction of nearly 77% from the single-phase converter at 30kW operation for a fixed output capacitance. Figure 2 shows schematics of the single-phase converter topology and its corresponding two-phase interleaved implementation.

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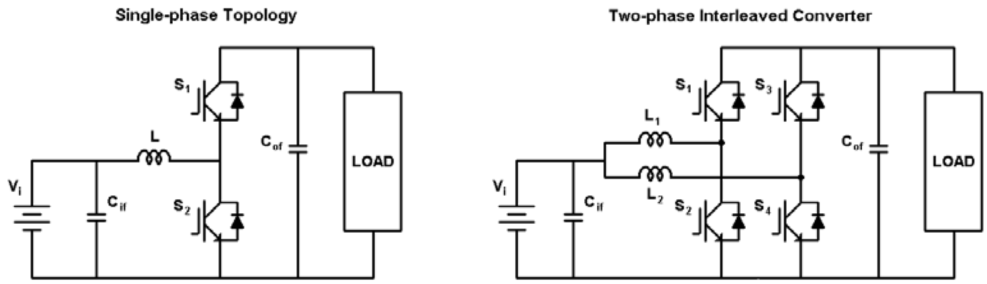

Fig. 2. Single-phase topology and two-phase interleaved converter schematics.

The two-phase converter was designed to operate in discontinuous conduction mode (DCM) over the entire 0-90kW load range. Isolated gate drivers for 300A dual IGBT modules, and inductors of 28uH, rated at peak currents up to 288A were built. The converter switching stage was mounted on a preliminary forced-air cooled heat sink for testing at low-to-intermediate power levels, while an oil-cooled heat sink designed for 80ºC (inlet temperature) oil was designed.

3. CONVERTER EVALUATION

During initial open-loop evaluation of the converter, results indicated that gapping of the inductor ferrite cores produced larger than predicted fringing flux that generated excessive eddy currents and significant losses in the inductor windings. The inductors were redesigned using new KoolMu® distributed-gap E-cores to resolve the fringing effect and to increase maximum core flux density. Comparison tests using KoolMu® cores showed a 73% reduction in winding temperature rise for 5kW, 15 minute, single-phase, buck mode operation. With the redesigned inductors, the converter was tested in open-loop, two-phase interleaved buck mode up to a nominal power level of 25kW and a corresponding efficiency of 92.4% at maximum IGBT operating temperature.

The converter was tested at higher power levels using a temporary under-sized oil-cooled manifold before fabrication of the final oil-cooled heat sink was completed. Tests were conducted using Castrol 399 coolant at an inlet temperature of 25°C and flow rates ranging between 1.5 and 2.5 gpm. Nominal output power levels of 50kW were achieved at maximum IGBT operating temperature for two-phase interleaved operation in both buck and boost modes at efficiencies of 95.2%.

As previous simulations had indicated, it was verified that the boundary between DCM and continuous conduction mode (CCM) operation would be reached at a power level less than 90kW. The transition would provide few adverse effects under open-loop testing, but would complicate closed loop control implementation. IGBT turn-off losses, which are known to be the dominant component of device power dissipation at high switching frequencies, ultimately prevented higher power levels from being demonstrated in the first prototype. The preliminary design as tested, using commercially available components, with provision for control hardware including sensors had an estimated power density of 2.7kW/L. Although this figure is approximately one-third of the target power density of 8.3kW/L, it showed significant progress toward the final system goals and provided valuable insight to existing technology weaknesses for FCS power conversion systems.

CONCLUSION

Based on the data gathered during the prototype converter evaluations, each of the system's power components is currently being improved under an Army technology development program (STO III.LG.2004.03/ Hybrid Electric FCS for Increment II). The inductors are being magnetically and thermally redesigned. Inductance will be reduced, and one of two designs will be pursued involving either planar core geometries or a cooling manifold fitted to the existing cores with thermally conductive material inserted between the cores to enhance heat removal. The power stage is being fitted for faster commercially available IGBTs with higher current ratings and reduced thermal resistance. An initiative is also being undertaken to develop IGBT modules equipped with higher rated anti-parallel diodes and an integrated liquid cooled base plate. Modeling has been conducted to investigate a variable frequency control scheme that would allow discontinuous operation in both buck and boost modes, while significantly reducing IGBT power dissipation resulting from turn-off losses at high power levels. Also, requirements of high and low side bus capacitors have been specified to achieve maximum 1% bus ripple voltages and operate at an ambient temperature exceeding 105°C. Following successful open-loop evaluations, closed-loop control will be developed.