Evaluation of Infineon HybridPACK^{TM} Drive with Optimized Integrated Capacitor/Bus DC Link for High Performance Inverter Applications

Michael Brubaker, SBE Inc., USA, MichaelB@sbelectronics.com

Terry Hosking, SBE Inc., USA, TerryH@sbelectronics.com

Michael Mazzola, Energy Production and Infrastructure Center, University of North Carolina at Charlotte, USA, mmazzola@uncc.edu

Somasundaram Essakiappan, Energy Production and Infrastructure Center, University of North Carolina at Charlotte, USA, Somasundaram@uncc.edu

Ehab Shoubaki, Energy Production and Infrastructure Center, University of North Carolina at Charlotte, USA, eshoubak@uncc.edu

Madhav Manjrekar, Energy Production and Infrastructure Center, University of North Carolina at Charlotte, USA, mmanjrek@uncc.edu

Tomas Reiter, Infineon Technologies AG, Germany, Tomas.Reiter@infineon.com

The Power Point Presentation will be available after the conference.

Abstract

The Infineon HybridPACK^{TM} Drive module was previously evaluated using the SBE 700A186 (500µF and 500V) capacitor/bus DC link [1]. This testing demonstrated the importance of low equivalent series inductance to achieve maximum efficiency with fast switching at full voltage, but test equipment was limited to 50kW. Power testing up to 150kW is now performed using both 750V and 1200V IGBT versions of the HybridPACK^{TM} Drive along with the 500V and 750V variants of the SBE capacitor/bus test kit. This work provides critical thermal data to establish a high performance inverter baseline that can be directly compared to silicon carbide modules which are planned for the HybridPACK^{TM} Drive package in the near future.

1. Introduction

The Infineon HybridPACK^{TM} Drive represents a significant improvement over conventional switch module technology [2] with a 30% smaller footprint, lower internal equivalent series inductance (ESL), and improved heat transfer from the terminals. Previous evaluation of this module with an optimized DC link capacitor/bus (SBE 700A186) has demonstrated improved efficiency with fast switching at full working voltage [1]. However, this testing was limited by the available load to less than 50kW, which did not fully exercise either the HybridPACK^{TM} Drive or capacitor/bus DC link to their expected capabilities. Scaling of the 50kW results indicated that this inverter should be able to operate in the neighborhood of 150kW with proper cooling.

This paper revisits the optimized inverter evaluation using test facilities at the Energy Production and Infrastructure Center (EPIC) at the University of North Carolina Charlotte with capability up to 150kW. Infineon has supplied HybridPACK^{TM} Drive modules, gate drivers, and controllers for testing up to 500V and up to 750V with SBE providing 500V (700A186) and 750V (700A245) capacitor/bus variants. Note that 750V operation is becoming highly relevant for the electric vehicle industry and a high performance inverter must be validated to address this market need. Note further that the 750V cap/bus (700A245) has a lower capacitance of 260µF as compared to 500µF for the 500V version which needs validation from a control perspective. The capacitor dielectric is metallized polypropylene (MPP) for all of the configurations.

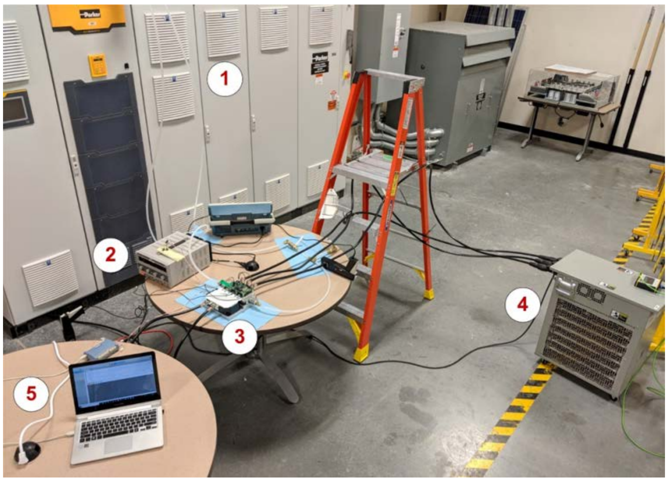
The 750V DC link cap/bus was simulated to look at the capacitor hotspot temporal evolution subject to thermal boundary conditions, ripple current, and DC bus current. Full inverter testing has been performed at EPIC to determine the capacitor, bus bar, and IGBT module hotspot temperatures subject to continuous full load with defined boundary conditions for the 500V and 750V inverter variants. Understanding the thermal time constants of the system is essential in order to define practical ratings for actual drive cycle conditions. This testing provides a high performance baseline for the HybridPACK™ Drive combined with optimized SBE capacitor/bus DC links.

2. Testing

2.1. Setup

A HybridKIT™ Drive which utilizes HybridPACK™ 1.2 kV-rated power semiconductor modules was supplied by Infineon. The power modules, along with the gate drive and controller boards were supplied mounted on a cooling plate. The drive was mated to the SBE-supplied DC link capacitor-bus (700A245). An aluminum adapter added to the cooling plate of the IGBT module enables mounting the capacitor case to the cooling block such that a thermal reference is defined. The capacitor-bus 700A245 consists of two windings which are connected in parallel to provide an effective capacitance of 260μF. Note that each winding is an SBE Power Ring Capacitor™ having a height of 30mm and an outer diameter of 76mm. The ac drive three phase outputs are connected to a resistive load bank rated up to 100 kW at 480 V line-line voltage. The cooling block is coupled to a chilled water coolant system which regulates the treated chilled water around a set point of 18.3°C. The experiment was performed in a lab where the ambient temperature set point is 22°C.

Each winding in the 700A245 cap-bus has three thermocouples for temperature readouts: one at the mid-plane of each winding inside the core, and one on each face of the winding. Thus the entire capacitor bank is provided with six thermocouples. These are connected to a data acquisition device and data logging computer and assigned a sampling rate of 0.5 Hz. The overall setup of the experiment and a close-up view of the DC link cap/bus and HybridKIT™ drive system are described in Fig 1 and Fig 2.



1 – Parker Hannifin Active Front End rectifier power supply; 2 – Benchtop control power supply for HydridPACK (12V); 3 – SBE 700A245 and Infineon FS380R12 HydridPACK Drive; 4 – 100 kW rated resistive load bank; 5 – Data acquisition unit and logging computer.

Fig. 1. Complete testing setup for Infineon HybridKIT™ drive and SBE cap-bus system at the Energy Production & Infrastructure Center at University of North Carolina at Charlotte.

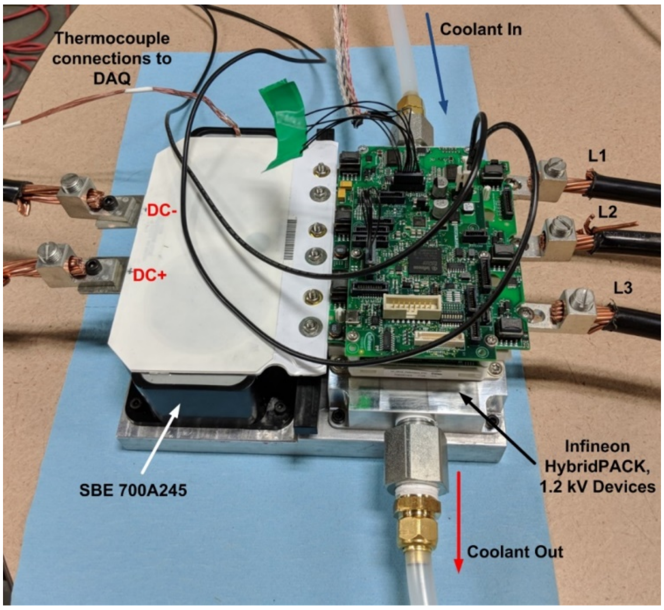


Fig. 2. Detailed view of Infineon HybridKIT™ drive and SBE cap-bus system connected to DC input power supply, load bank, coolant system and thermocouple data acquisition.

The HybridKIT™ drive was operated in the evaluation mode, with an input DC bus voltage of

714 V and at an output power level of 90 kW, and device switching frequency of 8 kHz. Note that the testing thus far has been performed using a resistive load where previous work utilized an RL load [1]. The capacitor ripple current is dominated by the switching harmonics, so the lack of an inductive component in the load is expected to have a minimal impact on the capacitor thermal performance. In fact, the resistive load scenario with no filtering can be argued to be the worst case condition.

2.2. Results

Initial testing has targeted 100kW in order to provide a baseline for later scaling to the 150kW goal. The cap-bus and HybridKIT™ setup was operated at 90 kW power level for 2500 seconds. Fig 3 shows the scope captures of the dc input current waveform from the power supply to the cap-bus, and also the ac output current waveform through the resistive load. The observed output ac rms current and voltage were 111.1 A and 472.4 V, yielding a processed power of over 90 kW.

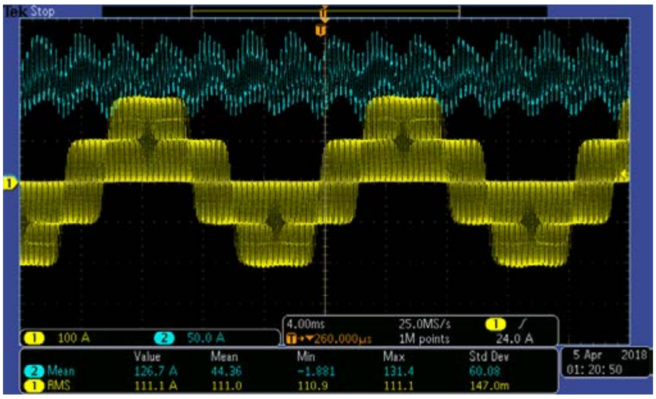


Fig. 3. DC input current waveform from the power supply to the capacitor bus (Channel 2, cyan), and ac output load current waveform (Channel 1, yellow), while the system operates at 90 kW power level.

The measured data from the six thermocouples in the two windings of the capacitor-bus are presented in Fig. 4. Some of the thermocouple data exhibited noise which was filtered out by removing the extreme outlying values from the analysis. It can be observed that the two core winding thermocouples data follow similar upward and downward trajectories, which is also true for the bus-side thermocouples and the case-side thermocouples.

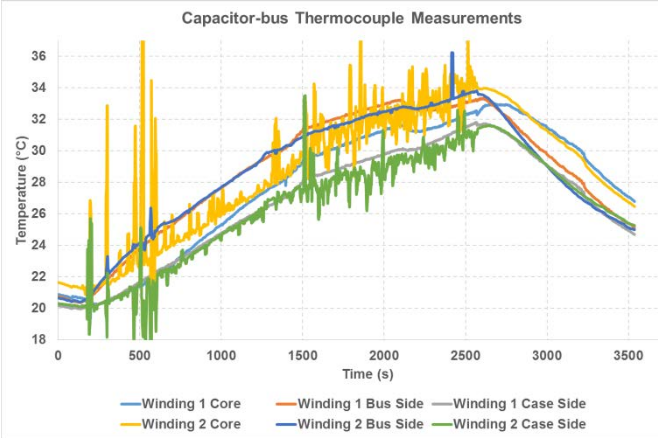


Fig. 4. Capacitor-bus thermocouples measured data for 90 kW operation. Some of the thermocouples exhibited noise in their outputs which was filtered out.

3. Simulation

3.1. Description

The simulation approach is similar to that described previously for the SBE 700A243 (500µF and 500V dual inverter) cap/bus [3]. The full capacitor and bus bar geometry was imported into the Flux3D™[4] finite element analysis package. Volume regions were defined to describe the windings, terminals, case, and potting components along with the bus conductors. The complete geometry and associated mesh is shown in Fig. 5.

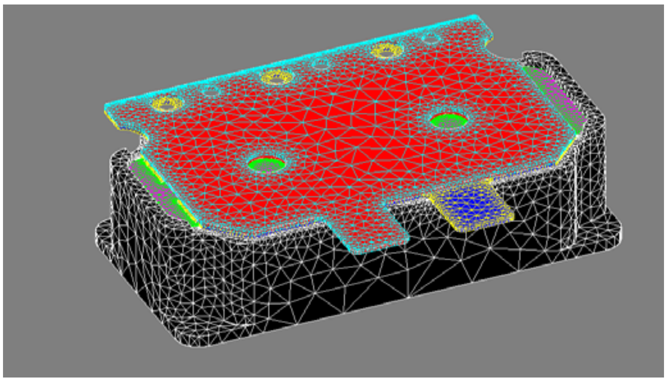


Fig. 5. Illustration of the finite element analysis domain for the 700A245 cap/bus.

The domain was first analyzed for a DC conduction scenario to determine the ESR of the bus bars and terminals. The bar bars source DC directly to the inverter along with ripple current from the capacitor windings while the capacitor terminals provide ripple current to the bus. Note that for this analysis the capacitor windings are simply treated as lumped resistive elements. The resulting DC ESR values for the bus conductors and capacitor terminals are scaled appropriately with temperature and frequency to provide input to the thermal analysis.

The full thermal model incorporates the terminal losses from the static analysis along with the spatial capacitor losses which include the Ohmic losses in the metallized film along with the dissipation losses and the DC leakage losses in the polypropylene film dielectric. The capacitor losses are computed using a proprietary tool which includes measured thermal properties along with temperature and voltage scaling. The thermal model can be exercised as a static simulation to compute the temperature distribution at equilibrium or as a transient simulation to look at the temporal evolution. Fixed temperature or convection boundary conditions are applied to the case and bus. A thin region model is used to treat the Mylar™ insulation between the bus conductors to avoid a locally dense mesh that consumes significant memory and suffers from convergence problems.

The actual test part was instrumented with thermocouples mounted at multiple locations in the capacitor/bus structure. Each winding has thermocouples located on each face (mirror images) and also inside the hollow core. Note that the “top” thermocouple on the winding is defined by the face of the winding closest to the bus. Sensors were built into the finite element model at the same locations to allow direct comparison with the measured data.

3.2. Results

The 700A245 is intended to support 750V DC link operation to reduce the current required to achieve the same power. The higher voltage requirement forces a lower capacitance in the same volume since a thicker film must be used. As such, the ESR of the capacitor is increased and the current rating will drop. Fortunately, the higher DC voltage reduces the DC bus current and the capacitor ripple current.

Consider a test case where the inverter operates at 97.5kW continuous power with a 750V DC link voltage. Scaling the previous results for the 700A243 operating at 500V [3], the capacitor ripple current and DC bus current will be 100Arms and 130A, respectively.

Some very useful insight can be derived by comparing the temperature profile evolution for the following three scenarios:

1) Capacitor winding losses only with 65°C boundary on the bottom of the capacitor case (Case 2).
2) Capacitor winding, bus, and terminal losses with 65°C boundary on the bottom of the capacitor case (Case 2a).
3) Capacitor winding, bus, and terminal losses with 65°C boundary on the bottom of the case and natural convection boundary (h=5) on the top surface of the bus. (Case 2b).

The results for each case are compared in Fig. 6 with 1) represented by squares (Case 2), 2) by diamonds (Case 2a), and 3) by circles (Case 2b). In each scenario, the blue curve corresponds to the sensor location in the core of the winding, while red and green represented the top and bottom winding face locations.

These results illustrate some important points in understanding the capacitor hotspot temperature relative to boundary conditions. First, the winding losses are the largest contributing factor to the overall capacitor hotspot temperature rise. Second, even though the bus losses are a relatively small fraction of the total losses, the temperature rise impact is significant for case side cooling where the bus heat must flow through the capacitor assembly to the boundary condition. This actually shifts the hotspot to the top of the winding. Third, even a minimal amount of bus cooling via free convection significantly reduces the hotspot temperature. In this case, the heat generated in the bus does not flow through the capacitor, and the capacitor windings are essentially given double ended cooling through the bus and crown terminal. Having defined these scenarios, the results can be readily applied to the test data.

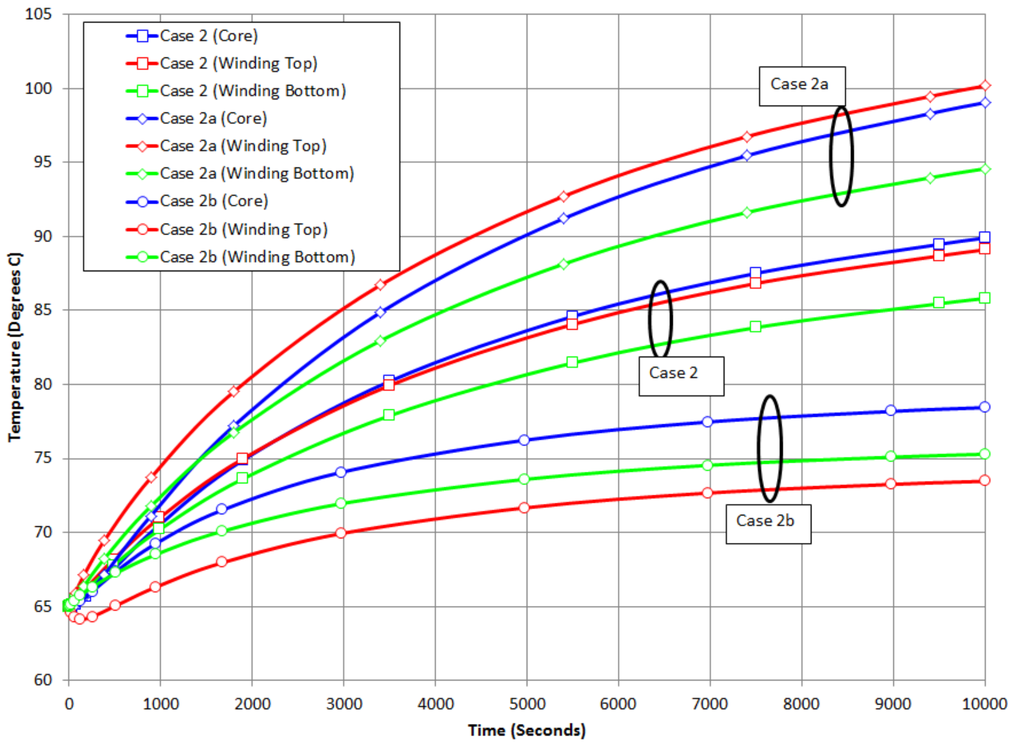


Fig. 6. Test case for 700A245 with different thermal boundary conditions.

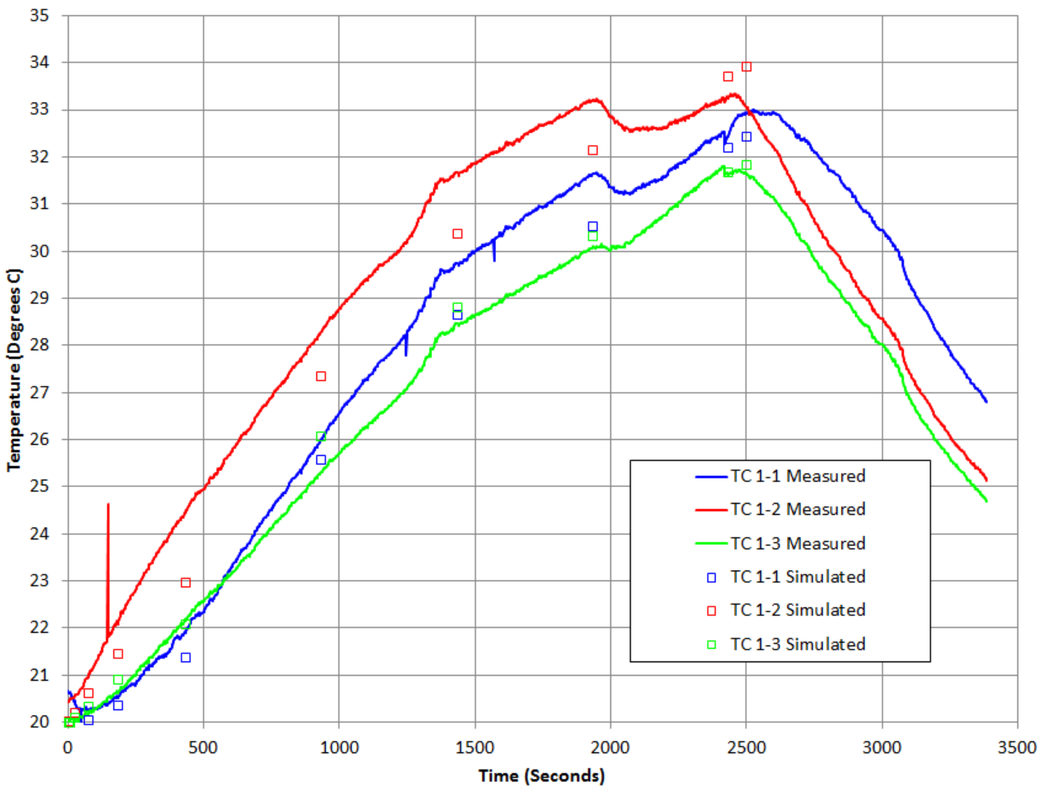


Fig. 7. Comparison of winding thermocouples and simulation results for the 90 kW test run.

4. Discussion

With regard to the DC link capacitor, the test results correspond to “fingerprint” of case 2a from the simulation (case side cooling with bus terminal and winding losses). Adjusting the loss calculations to match the test parameters and accounting for the increase in the coolant outlet temperature over the test, a good correlation is observed as shown in Fig. 7. The hotspot occurs at the top of the winding adjacent to the bus since the dominant cooling path is through the relatively large thermal resistance of the plastic case wall. These results are significant in that the hotspot temperature rise with this pessimistic cooling condition is less than 15^{o}C operating at 90kW for 2500 seconds. As such, 100kW continuous operation can be supported with this configuration with a coolant temperature up to 85^{o}C to achieve typical power train component life requirements (e.g. 10,000 hours). With bus side cooling employed, the DC link can easily manage continuous 125kW operation short duration peak power beyond 150kW. Note that the limit during peak events can actually be bus bar heating via DC current rather and the capacitor temperature rise due to ripple current [3].

It is important to note that the capacitance reduction (500µF to 260µF) in scaling the DC link from 500V to 750V with the same weight and volume is not limiting the inverter performance. The corresponding reduction in both bus and ripple current due to increasing the DC voltage results in a safe thermal operating condition even with the worst case cooling scenario. The question is thus the minimum capacitance required for control stability and acceptable voltage ripple rather than the capacitor ripple current limit.

Additional testing is needed to evaluate the overall efficiency of the inverter. A new load will be available soon to support future testing up to 150kW, which will allow a very useful comparison of scaling. This is important to determine the ultimate limit of the DC link versus the actual IGBT module. The use of intelligent gate control balanced with a low commutation loop inductance remains critical to obtain the best possible system performance [5, 6].

5. Conclusions

A high performance inverter based on the Infineon HybridKIT™ with a HYBRIDPack™ Drive module has been evaluated using the SBE 700A245 cap/bus DC link (260µF at 750V). Safe continuous operation at 90kW for 2500 seconds has been demonstrated with the capacitor cooled only from the plastic case, which is the most pessimistic condition. The 90kW data has defined a scalable foundation for moving to the 150kW testing target which is now in progress. This work will establish a critical baseline to enable an objective comparison of Si versus SiC devices using the Infineon HybridPACK™ Drive module with the same inverter topology.

6. Acknowledgements

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7. References

[1] M. A. Brubaker, T. A. Hosking, T. Reiter, M. S. Chinthavali, and L. D. Marlino, “Optimized DC Link for Next Generation IGBT Modules”, Proceedings of PCIM 2016, Nuremberg, Germany, May 16-18, 2016.

[2] Infineon, “Compact Power Modules”, *Electric & Hybrid Vehicle Technology International*, July 2014.

[3] M. A. Brubaker, T. A. Hosking, W. Liu, T. Reiter, C. Wust, and D. Kuschnarew “High Performance DC Link Capacitor/Bus Sourcing Dual Infineon HybridPACK™ Drive Inverters for EV Applications”, Proceedings of PCIM 2017, Nuremberg, Germany, May 16-18, 2017.

[4] Altair, 164 Indusco Court, Troy, Michigan, 48083, www.altair.com

[5] M. Mazzola and J. Gafford, “Integrating Depletion-Mode SiC VJFETs into Production Motor Drives” Proceedings of PCIM 2016 PCIM, Nuremberg, Germany, May 2016.

[6] M. Mazzola, J. Gafford, and B. Sullivan, “Safe Integration of Depletion Mode SiC VJFET Power Modules into a Commercial Motor Drive,” Workshop on Wide Bandgap Devices and Applications (WiPDA), Albuquerque, NM, Oct. 30- Nov. 1, 2017.