Progress On An Optically Interconnected, Heat Pipe Cooled, HVIGBT-Based Mega-Watt Inverter Building Block For DER Applications

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Abstract— **High power applications typically use power converters that are large, expensive, are difficult to control, and present significant engineering challenges as power density and power capacity increase. Additional problems include the complicated heat removal systems used to cool the power converter system, as well as the isolation requirements of the sensors used for protection and control. This paper presents the first optically interconnected, heat-pipe cooled, high-power inverter building block for distributed energy applications. The inverter design incorporates many recent advances in optical current, voltage, and temperature sensors, integrated heat pipe cooling systems, and High-Voltage Insulated Gate Bipolar Transistors. The integration of these subsystems, in combination with a "design for manufacturing" approach, has resulted in an extremely cost-effective topology that tremendously simplifies development within the high-power electronics environment.**

I. Introduction

THIS research effort has targeted issues that are impeding state-of-the-art, next-generation advances in power conversion technologies, specifically, the problems associated with existing higher-power systems and how they are applied to distributed energy resource (DER) applications. State-of-the-art converters have severe limitations due to one or more following:

- Slow switching speeds requires larger-sized passive components (a power density and cost problem),
- When turning off the opposite-side anti-parallel diode, the main switching devices cannot withstand high rates of current change (di/dt), and the design most often requires a series inductor along with a resistive-diode for current protection as well as some form of a voltage clamp circuit to prevent the device from over voltage failure,
- The requirement for external deionized (DI) water-cooling systems to dissipate heat due to switching and conduction losses. These systems have high life-cycle maintenance costs and reduce overall system reliability,
- The physical size of existing systems often prevents their wide-scale deployment in space critical applications, such as those on board ship, aircraft, or spacecraft (the power density problem),
- High-power conversion systems are largely based upon smaller conversion systems with applied scaling rules, e.g., a 5-MW system ~ size of 10, 500 KW systems,
- The lack of availability of optical sensors involved in the control and protection loop results in decreased reliability due to increased susceptibility to noise affects,
- High-power converter systems are not "generic", so economies of scale due to manufacturing and procurement are extremely difficult to achieve.

The list continues to expand as increasing pressure is placed upon manufacturers to deliver smaller, faster, and higher power converters for an ever-growing list of demanding applications. To combat these limitations and to enable the creation of efficient, reliable, high-powered converters, a new generation of power stage technology has been developed. Specifically, these power stages are optically interconnected, are based upon the latest Insulated Gate Bipolar Transistor (IGBT) technologies, and use innovative self-contained cooling technologies to provide extremely compact and reliable systems. The advantages of implementing all-optical sensor and feedback schemes, when combined with all-optical gate drive control signals in high-power converters are numerous: the high-power output stage can be completely isolated from the lower-potential input and control subsystem, resulting in higher reliability, reduced personnel hazard, and simplified gate control implementation. Furthermore, the compact design afforded by the integrated heat pipe cooling solution, as well as a 'design for manufacturing approach', has resulted in a fundamental building block that will allow standardized, reduced footprint implementation of high-power converters.

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II. SYSTEM COMPONENTS

A. IGBT Technology

Mitsubishi produces multiple High-Voltage IGBTs (HV-IGBTs) with different ratings that occupy standard 190mm x 140mm footprints. A photograph of the device is shown in Figure 1. The voltage/current rating of these CMxx00HB devices varies from between 1700V/1800A to 4400V/900A. Heat due to switching and conduction losses is removed from the base of this device, and low-inductance/high capacitance planar bus interconnection is enabled on the opposing (exposed) side. This flexibility allows the switches to be sized to the application without changing any other system component while permitting the development of scalable phase legs. Low inductance/high capacitance planar bus topologies result in lower overshoot of switching voltages and currents, further reducing the need for additional protection devices. Furthermore, the use of these HV-IGBTs switches permits higher switching frequencies, and although switching losses increase as a function of switching frequency, aggregate losses are lower.

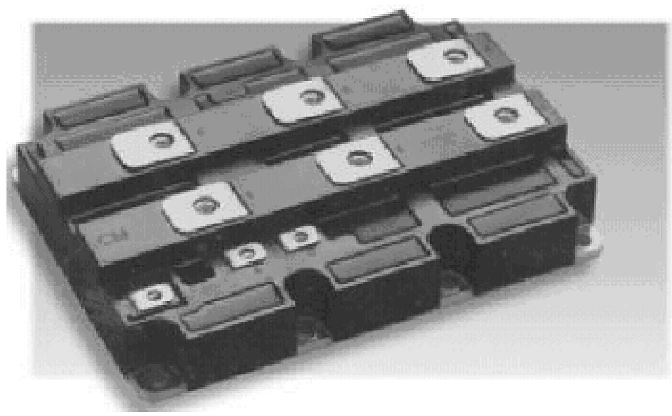

Figure 1. Mitsubishi CMxx00HB HV-IGBT package selected for this research. The flat-top allows for a low-inductance/high capacitance planar bus design while permitting heat due to switching losses to be removed from the base.

B. Optical Interconnection and Sensing Technologies

Optical gate drive interconnects have been used in converter designs for over 15 years. The resulting noise immunity from switching energy, isolation from high voltages, and the ability to increase packaging density are well established.

The use of conventional sensor technologies in converter design, especially as power densities increase, presents the system designer with several challenges. First, traditional thermistor or resistive temperature devices (RTDs) require significant isolation when connected to the high-power stage. Often, an analog-to-digital converter (ADC) and microprocessor combination are located on or near the gate driver board (referenced to the high-voltage level) to convert the temperature into a digital value, which is then linked to the control and protection function via optical fiber. Second, the use of isolated Hall-effect current transducers (CTs) to monitor load current complicate the design in requiring a source current be provided to the CT, which is often located very near the high voltage section. Difficulties with electromagnetic interference (EMI) caused by switching energy, as well as power supply and signal processing requirements, make this a challenging approach. Correspondingly, the same holds true for potential transformers (PTs) and their use in high-voltage monitoring.

Optical sensor technologies have been developed on this program that overcome many of the design limitations presented by conventional sensor technologies. The developed power conversion system utilizes optical temperature and current sensors that perform with equivalent accuracy to conventional sensors while providing the intrinsic benefits of voltage isolation and natural noise immunity. Locating the temperature sensors directly on the HV-IGBT or planar bus provides immediate indications concerning the performance of the cooling system. The optical current sensors are located on the circular conductors connecting the load to the planar bus and provide a direct indication of the load current being supplied by the phase leg. Optical voltage sensors are under development and will be implemented as the voltage sensor technology matures.

C. Heat Pipe/Forced Air Cooling

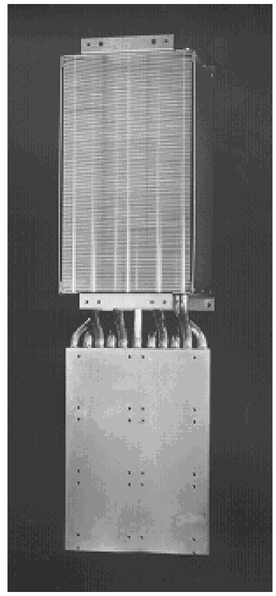

Figure 2. Model 835 heat pipe assembly used in the power conversion phase legs. Heat forces water to a vapor phase, where it rises into the cooling assembly. Fans (not shown), blow air across the cooling fins, causing the water to condense and flow back to heat bar.

The developed three-phase power conversion system uses six (6) modified Model 835 ThermaCharge heat-pipe cooling systems from Thermacore of Lancaster, PA. Two HV-IGBTs are mounted on each 835. Each phase leg incorporates two 835's to provide a total of 20,000 watts of heat removal capacity. A total of four (4) high-reliability fans are associated with each phase leg, providing cooling redundancy in the event that one fan fails. Unlike conventional deionized water-cooled systems, the system can operate in a degraded mode in the event of loss of one cooling fan. Nominal operating range for the 835s is from 40°C to 180°C with water as the standard internal cooling fluid. The 835 operates on a principle of heat removal by transitioning water from a vapor phase to a liquid, hence operation of the 835's was a concern at non-vertical orientations. The modified 835's in use have been tested to remove 8250 watts of heat (a 43°C change in input to output air temperature) at an inclined angle of 83° from the vertical. This was deemed adequate for all applications on moving platforms, such as naval ships or other mobile platforms.

The intrinsic cooling system afforded by the 835 has several advantages compared to conventional deionized cooling systems. First, considerable life cycle cost reduction can be realized by this type of system, namely in the form of reduced expenditures on parts and maintenance. Second, higher reliability is realized since there are fewer components to fail, especially in high-vibration environments. Third, the small footprint offers a compact design for space-constrained applications. Additionally, maintenance and repair of the system is made much easier since there is no water manifold to work around nor is there the requirement of draining the system prior to beginning work.System Configuration

D. Single Phase Topology

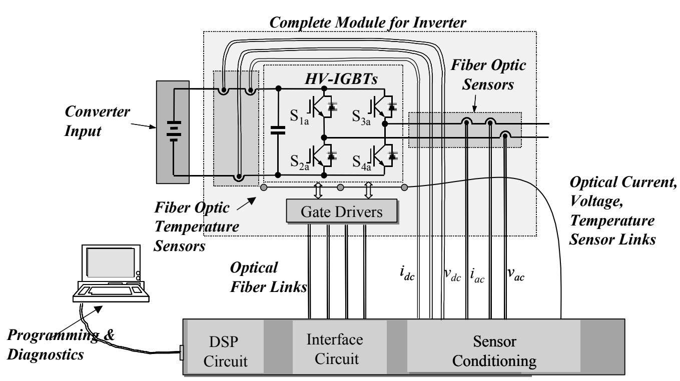

Figure 3. Single-phase system configuration. Topology is unique in that there is complete optical isolation between the higher power H-bridge and the low-power conditioning and control system.

Figure 3 shows the electrical topology of a single phase leg. DC power is provided at the converter input and can be different forms of DER – fuel cells, chemical storage, a direct DC link from a rectifier, etc. It is currently planned to instrument the input DC link with optical current and voltage sensors. The DC link is connected across four HV-IGBTs in a standard H-bridge configuration – this topology was selected so that a phase-leg stage could become a basic building block of a multi-level cascade system of higher power capacity. The HV-IGBTs are controlled by gate drivers that are connected via multi-mode plastic optical fiber to the low-power interface subsystem. The AC output is instrumented with fiber optic sensors, thus providing complete monitoring isolation between the high-power stage and the low-powered control system. Optical temperature sensors are mounted directly to a witness IGBT or directly to the high-voltage planar bus at predetermined locations and are directly connected to the low-power signal conditioning equipment. The output of the optical sensors is processed and fed directly to a TMS320C2407 DSP that performs all control and protection functions for the phase leg.

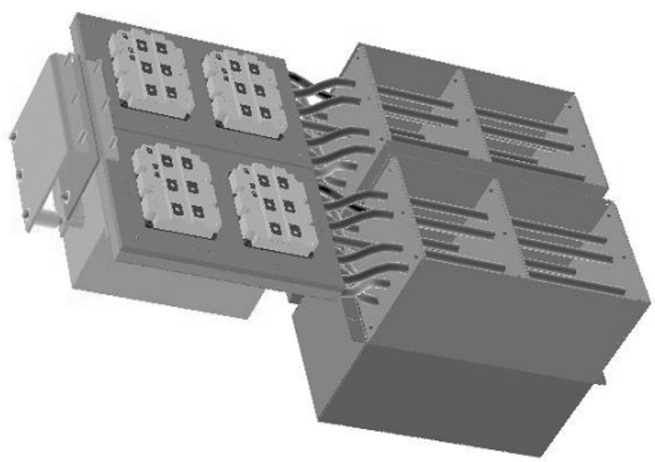

Figure 4. Single phase HV-IGBT H-bridge configuration. Each phase leg is comprised of two 835s with a total of four HV-IGBTs. A low-inductance/high capacitance planar bus (not shown) lies flat on the IGBTs and connects the filter capacitor (behind the HV-IGBT cooling plate) via a six-terminal copper bus assembly.

Figure 4 shows the single-phase hardware configuration. Four HV-IGBTs are distributed on a thick-block copper heat sink that contains the heat pipe technology. A low inductance/high capacitance planar bus mounts flush on top of the HV-IGBTs and provides the method to connect the load to the switches as well as connecting the DC link and filter capacitor to the system. The entire assembly of two modified ThermaCharge 835s is installed in a standard 37"x 24"x 53" rack system.

E. Three Phase Realization

Figure 5. Three-phase H-bridge inverter showing complete cooling solution and exposed HV-IGBTs.

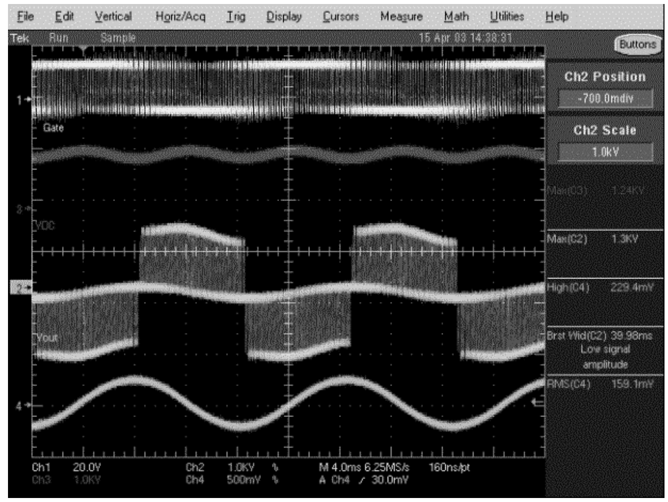

Figure 6. Representative single-phase waveforms.

Figure 5 shows the relative size of the complete three-phase megawatt-level inverter system. As can be seen the three assemblies are extremely compact, allowing their deployment in space-constrained applications. The entire three-phase assembly weights approximately 1450 lbs as shown and has overall dimensions of 37"x73"x54". Addition of the planar bus assemblies, as well as control and protection subsystems will add another 25-30 pounds to the system.

III. Preliminary Cooling System Performance Data

Each phase leg is designed to remove 20,000 watts of heat generated by switching and conduction losses from the HV-IGBTs. The modified ThermaCharge 835s have been tested to 8250 watts each (16,500 watts per phase leg) by Thermacore and produced a 43°C rise between input ambient air temperature and the exhaust air temperature. Several factors may influence whether final implementation of the system will actually support the 20,000 watt heat removal target: heat transfer resistance from the HV-IGBT to the 835s, HV-IGBT location on the 835s, and thermal efficiency of the 835 heat block to dissipate the heat source across all heat pipes. Careful monitoring of the HV-IGBT case temperature using fiber optic temperature sensors is required to ensure that the HV-IGBT maximum junction temperature of 150°C is not exceeded.

Ultimately, thermal efficiency of the cooling system dictates the final total power that can be drawn from the source and (less losses) delivered to the load. 1700V/1800A switches, operating at 60% capacity to allow ample operating margin will permit individual phase loads of ~1.8MW. 4400V/900A switches, again operating with the same 60% margin could see individual phase loads of 2.3MW. At a maximum heat removal capacity of 20KW per phase the required efficiency of the system must be 98.9% and 99.1% respectively, which likely is not attainable with a hard-switched pulse-width modulation (PWM) or space vector modulation (SVM) control algorithm.

TABLE I
PER PHASE RATING AS A FUNCTION OF HEAT REMOVAL CAPACITY

Efficiency	Per Phase Capacity
95%	400 KW
96%	500 KW
97%	667 KW
98%	1,000 KW
99%	2,000 KW

(Based upon 2,500V/1200A CM1200HB-66 HV-IGBT switches, 20,000-watt heat removal capacity, and a 60% rated specification operation level.)

Table 1 presents per-phase benchmarks for different efficiencies of the system. As can be seen, considerable benefit exists for slight improvements in efficiency, especially at higher power levels.

In order to establish an operational baseline, a single phase leg was tested in open-loop configuration with a 10mH reactor as the load. The control algorithm was standard hard-switched PWM with a modulation level of 70%.

Figure 6. shows a representative capture of the synthesized voltage and current. The top trace is the PWM control signal for one HV-IGBT. The second trace from the top is the DC bus voltage and is indicating a level of about 1.3KV. The third trace is the output voltage and is indicating a voltage level of nearly 2.6KVpkpk. The fourth trace is the load current and is indicating approximately 180Apkpk.

Temperature rise of the exhaust temperature is plotted as a function of load current in Figure 7. Temperature increases roughly in a linear fashion through 250A, with a slight increase near the higher currents. The slope of the line is higher than what was predicted by thermal models and indicates that the heat transfer efficiency from the HV-IGBTs to the 835 heat block, as well as from the heat block to the heat pipes may be less than optimum.

Given that the temperature rise of the exhaust temperature was higher than predicted for a given current level, and that the junction temperature of the HV-IGBTs is a critical operational parameter, an effort was undertaken to locate the error source. It was determined that during the initial thermal analysis that the effects of heat generation from the HV-IGBTs as well as heat sinking from the heat block was not properly considered. The HV-IGBTs must be modeled as independent heat sources with thermal load densities that change as a function of their conduction current and switching loss. Relying solely upon conduction current pathways is not adequate to predict busbar or system temperature rise. The 835 heat block was also modeled with a thermal load density, but of negative sign relative to the HV-IGBTs. Furthermore, improvement resulted by introducing a 4°C thermal boundary differential between the bottom of the 835 heat block and the top, which closely resembles runtime performance. Figure 8 provides a conceptual setup of the thermal model initial conditions.

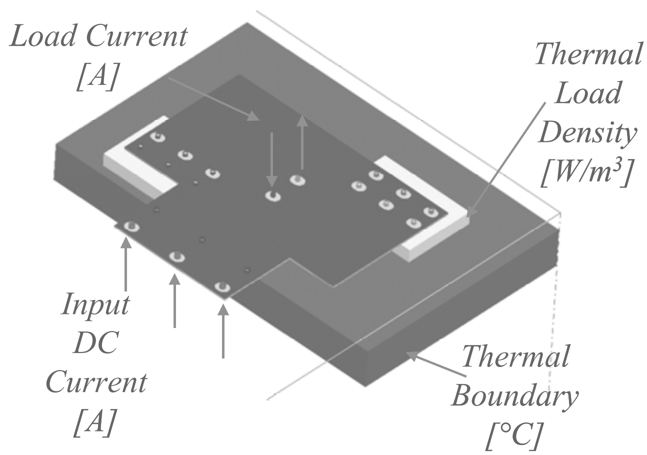

Figure 8. Schematic of thermal model initial conditions.

After several iterations and adjusting of the thermal model, convergence between the calculated and measured temperature on the HV-IGBT case was achieved. The results of this analysis are presented in Figure 9. The top trace shows the measured temperature, and the bottom trace shows the modeled (predicted) temperature. Close correlation, to within a few degrees at 250A RMS was achieved, resulting in a model with

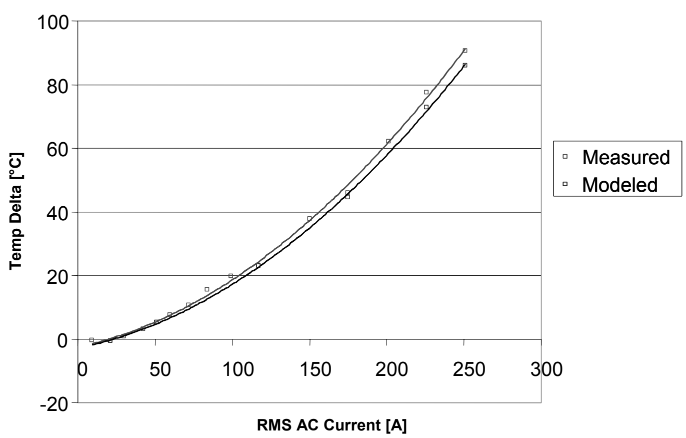

Figure 9. Measured vs. predicted HV-IGBT temperatures as a function of AC load current.

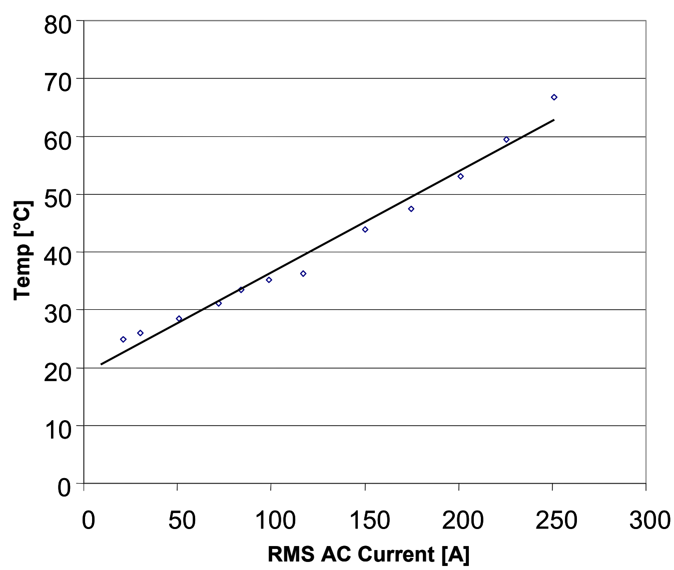

Figure 7. Cooling air exhaust temperature as a function of AC load current. The slope of the line is higher than what was predicted during thermal modeling of the system.

high confidence with respect to predicting overall HV-IGBT, heat-block, and exhaust temperatures. Establishing the thermal model is critical to success of the program due to the high capital costs associated with the high-power components as well as establishing space-cooling requirements.

Reexamination of the mounting procedures for the HV-IGBTs also revealed a potential error source. Initially, the HV-IGBTs were installed using a thermal compound as the interface between their heat plate and the 835 heat block. Review of the thermal resistance indicated that in standard applications typical compound values are on the order of 0.29-in^{2o}C/W, whereas new phase-change interface materials result in total thermal resistance values as low as 0.008 in^{2o}C/W. All future HV-IGBT installations will utilize these phase-change interface materials and results will be forthcoming.

IV. Conclusions

This paper reports the progress in the development of a modular building block power converter for high power distributed energy resource applications that uses heat-pipe technology for the cooling system and optical sensors for protection and control. To date (October 2003) a single-phase inverter system has been low power tested to 450KVA continuous using a reactive load, with promising results. Heat rise greater than what was predicted was observed and thermal models were revised to account for the discrepancy. New busbar and gate drive designs are being incorporated and tested to improve system thermal performance and overall reliability. New thermal management interface materials will be used in the system to affect greater heat transfer from the HV-IGBTs to the 835 heat plates. Assembly of the three-phase system continues and is expected to be completed early 2004. Continuous-mode low-power testing of the three-phase system using reactive loads will begin shortly thereafter, as well as full-power pulse testing. Full system results and conclusions will be published upon conclusion of the program, anticipated in mid-2004.