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Impact of cryogenic temperatures on high-power semiconductor performance

J. Kwon[1], M. Tomsic[2], E.W. Collings[1], M.D. Sumption[1]

[1]CSMM, MSE, The Ohio State University, Columbus, OH 43210, USA
[2]Hyper Tech Research Incorporated, Columbus, OH 43228, USA

Email: kwon.540@osu.edu

Abstract. Power electronics is necessary for the independent control of the stator windings of electric aircraft motors. The benefit of using liquid fuel to cool conductors to utilize their high current density has enabled power electronics to be cooled by proxy. While small scale semiconductors have been found to be degraded during operation at cryogenic temperatures, results for systems rated for high power cryogenic applications have not been explored as much. In this work we test the performance of IGBT power electronics from room temperature to 77 K, with a focus on temperatures expected for electric aircraft motors using liquid natural gas (LNG, BP about 120 K) as the cooling medium. In this work, the measure of performance was taken to be the ability to be turned on and off (switched) by an input signal provided by a function generator. We also tested the cold-start ability i.e., the lowest temperature in which the power inverter will start. The lowest cold-start temperature was measured as 140 K. Experimentally, we also observed that both conduction losses and switching loss from a low-power constant current with an operational frequency of 10 kHz were sufficient to allow the inverter to work down to 105 K (below the LNG boiling point).

1. Introduction

The electrification of aircraft is a necessary transition to meet the target of net zero emissions by 2050 set by the Paris Climate Agreement. Small electric aircraft make small contributions to aviation emissions most of which stem from large commercial aircraft [1]. Electrification of such aircraft requires high power density electric motors that do not yet exist [2]. The metric for determining the performance of electric aircraft motors is Power Per unit Weight (kW/kg). Conventional electric motor designs cannot meet the high-power density criteria required for aircraft, especially because a high-power density drive train must be achieved in tandem with high efficiency (>97%). One reason these two goals are required at the same time is because for every bit of efficiency loss, the amount of onboard fuel must increase for a constant aircraft range, and this would negate any weight savings from higher power density drive trains unless efficiency is maintained. With respect to aircraft propulsion motors, the windings can be made lighter by using Al instead of Cu (because of its lower density), and if we reduce the temperature of the windings, the lower resistivity can lead to both higher current densities (and thus less winding mass) and also higher efficiency (reduced ohmic losses) [3,4].

High power aircraft motors are presently being studied, funded by ARPA-E and NASA. A program underway at OSU and Hyper Tech Research Inc. (and funded by ARPA-E) uses cryogenic fuel (LNG) for cooling. Cryogenic fuel has the advantages of high energy density, cleaner emissions, and renewability. In addition, the motor takes advantage of "free" cooling to cool the conductors [5,6]. The conductors are cooled through direct contact with the cryogenic fuel, a situation where the electronics within the motor housing are cooled by proxy.

Under normal operation the conduction losses and switching losses generate enough heating to enable the inverters to operate temperatures close to room temperatures [7,8]. However, dangerously low cryogenic temperatures may occur when less than full power operation (hence a low rate of cryogenic fuel consumption) occurs. Various scenarios such as precooling the motor, low-power descent [9], or full power loss emergencies can be situations where the cooling capacity overwhelms the inverters and permanently damages them.

Early on, Si CMOS semiconductors were successfully tested down to 10 K, but they are outdated technology whose 1 μm channels and not rated for high-power applications [10,11]. More recently, modern commercially available inverters have been operated at temperatures down to 75 K with no permanent damage to performance [12–14]. However, the inverters tested were based on SiC and GaN semiconductors and were not rated for high-power operation.

In this study, we have tested commercially available high-power IGBTs that meet the specifications required of the motor at cryogenic temperatures in a half-bridge configuration. Our present designs call for using these SiC based IGBTs to develop the motor drive (inverters). The IGBTs were subjected to temperatures down to the temperature of liquified natural gas (LNG) at 120 K, and below.

2. Experimental

High-power inverter modules 2MBI800XNE120 from Fuji were tested at cryogenic temperatures. They were selected based on commercially available, compact IGBT modules that fit well in OSU's motor and inverter design package.

2.1. Test Set up

The inverter module was bolted to a 5 kg copper thermal sink. Apeizon grease was applied to the interface to enhance the thermal conductivity of the heat sinking fixture/IGBT interface. Two type E thermocouples were placed on the top of the thermal sink. On the bottom of the thermal sink, copper straps and nichrome wires were attached as shown in Figure 1. The straps provided conduction cooling to the thermal sink. They extend down to the bottom of the testing chamber and come in contact with pool-boiling LN2 (liquid nitrogen, 77 K). The nichrome wire served as a 20 W heating element, which allowed us to set the temperature of the system under test. The heating element was taped to the thermal sink and a layer of cigarette paper and varnish in between provided electrical insulation and good thermal conduction to the copper.

The ohmic heating (via the nichrome wire heating element) evaporated LN2 created a nitrogen gas filled, ice-free environment in the testing chamber.

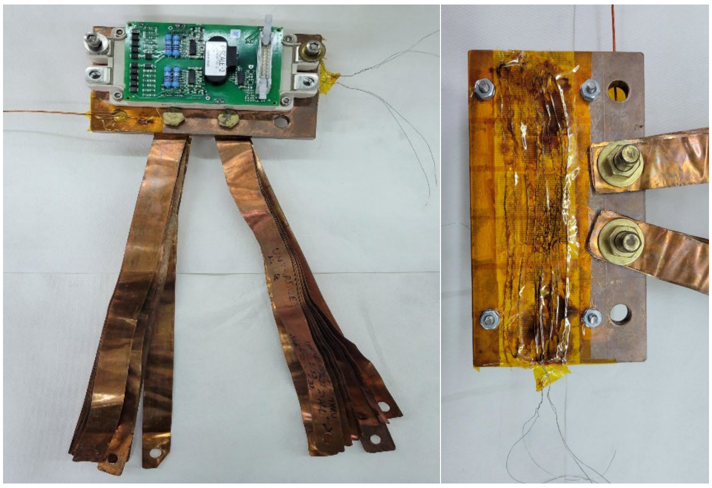

Figure 1: left) upright configuration of inverter module, right) underside nichrome wire configuration

2.2. Testing Procedure

To thermally test the functionality of the inverter, thermal cycling was performed using a cooling and warming rate of 5 K/minute and 3 K/minute, respectively. This first test stayed within the motor design expectations of operational temperatures above -50 °C. The temperature of the cold plate was cycled from room temperature, 27 °C, to temperatures between 0 °C and -50 °C at increments of 10 °C with a 5-minute hold at target temperature. Figure 2 shows the temperature vs time for each temperature cycle. Each cycle was repeated 5 times. The performance changes with each temperature decrease and repetition were monitored.

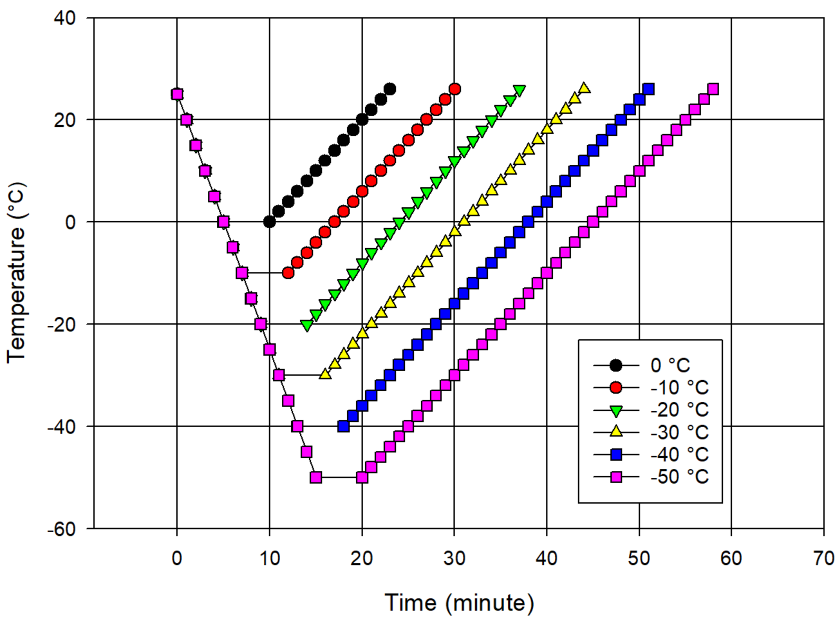

Figure 2: cooling time for each cycle.

We also tested the cold-start functionality of the power inverter from RT down to LNG temperature (120 K) (achieved by balancing LN2 cooling and heater power). A cold-start was defined as turning on and switching at a desired frequency from an off state. This removed any conduction or switching loss heat generated from continuous operation. After finding the coldest switching temperature, a constant on-state was conducted at low-power to test the low operational temperature boundary considering conduction and switching losses.

All inverter tests were conducted at low-power conditions of 5 V/5 A. This is considered low-power since the inverter is rated for 1200 V and 800 A. This criterion was set to avoid any heating elements that would allow the inverter temperature to deviate from the measured temperature of the cold sink. While the temperature sensor built into the power electronic device could in principle, provide a better temperature reading of the semiconductor chip inside, it is not rated for cryogenic temperatures and would not provide reliable readings down to LNG temperatures.

3. Result and Discussion

The initial thermal cycling test of the power inverter within manufacturer and motor design showed no permanent degradation of performance. However, an increase in overshoot voltage during step down was measured as the operating temperatures decreased as shown in Figure 3. This overshoot-voltage was mitigated at ambient room-temperature and cryogenic temperatures with the use of a snubber capacitor.

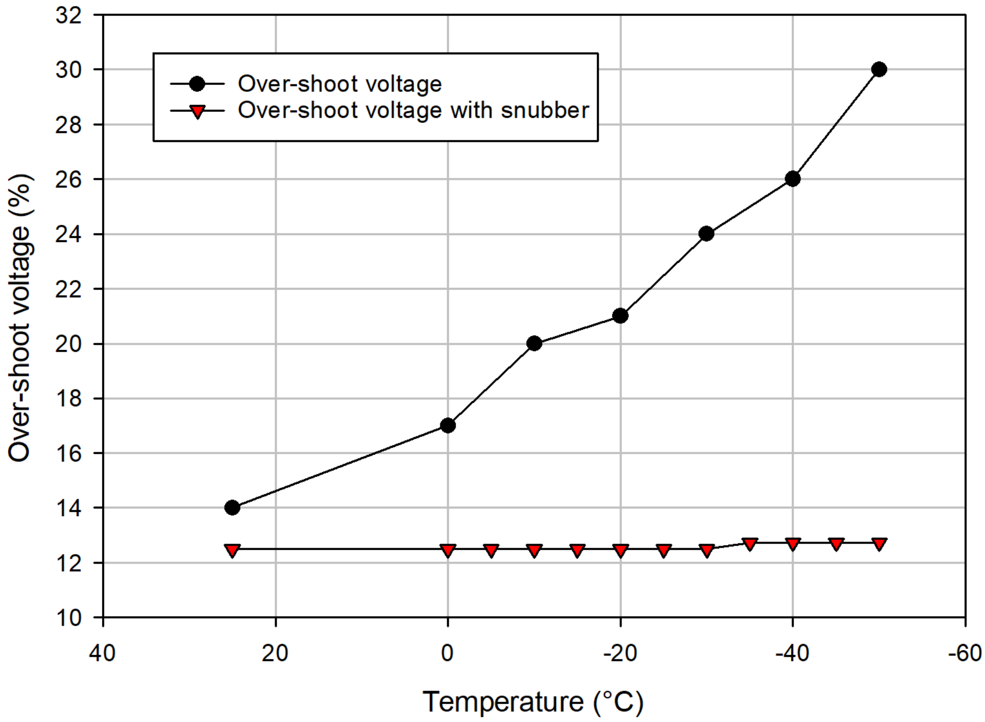

Figure 3: performance metrics from room temperature to -50°C

The second test demonstrated the cold start conditions beyond the inverters rated operational temperature (-50 °C). Figure 4 shows the change in temperature with time displaying a slow cooling rate and emphasis on thermal equilibrium in the system. Operational frequency of 1 kHz was chosen for the cold test to minimize any additional heating contributions such as switching losses that may unintentionally increase the temperature of the power electronics. The switching frequency for cold start operations have little effect on the results but we did not want to deviate too far from the intended operational frequency of the motor above 10 kHz. The cold start functionality persisted from room temperature down to 140 K, at which point an input signal did not produce an output signal. This operational range is shown by the black dots in Figure 4. Next, the persistent switching state was tested for 1 kHz and 10 kHz. The green line demonstrates the 1 kHz operating temperatures down to 135 K.

The teal line shows the 10 kHz operating down to 105 K, below the temperature of LNG. This shows that continuous switching mode at low currents is sufficient heat generation within the device to operate at temperatures even lower than the lowest cold start temperatures. This might lead to a case where, in the event of a full shut-down in an LNG cooled motor, the inverter submerged in 120 K liquid cryogen would not be able to conduct a cold start at 120K but will stay operating when continuous switching is maintained, even at low power conditions.

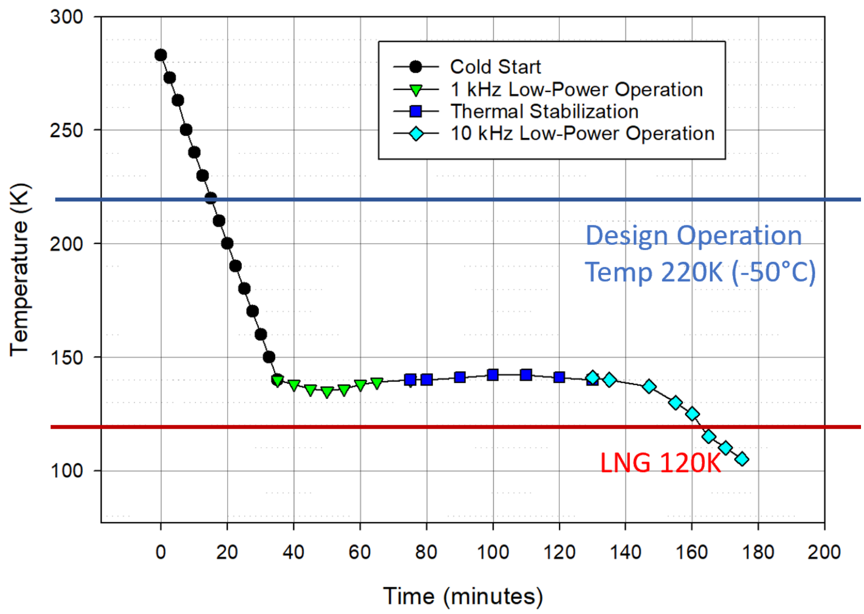

Figure 4: cold-start and persistent switching state operating temperatures

4. Conclusions

In this work we have performed cryogenic testing of high-power inverter IGBT modules 2MBI800XNE120 from Fuji. The IGBTs were tested from ambient down to 100 K at low power excitation (5 A/5 V). The main purpose was to see when the inverters stopped switching. To perform the test, we mounted the inverter to a Cu plate, and the plate was placed in an open dewar above a bath of LN2. Cu straps connected to the plate were draped into the LN2 providing cooling, and a Nichrome heater place on the Cu plate allowed us to heat the plate and inverter and control the temperature (monitored with thermocouples). We found that switching could occur at temperatures as low as 105 K, assuming 10 kHz, continuous operation. Using 1 kHz continuous operation, 135 K could be achieved. These lower temperatures were possible because of internal switch heating. If, however, we turned off the switching and then tried to re-start it, 140 K was the lower limit temperature. All of these temperatures are well below the rated lower bound of operation of -50°C. The tests were performed with a number of cycles, showing repeatability and a certain level of ruggedness. Our next steps are higher power testing, as well as thermal shock.

5. References

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