Cryogenic Power Electronics: Press-Pack IGBT Modules

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Abstract. With the goal of enabling high-power-density cryogenic power converter technology and superconducting power applications for future aircraft and shipboard power systems, the dynamic and static performances of a press-pack IGBT module (T0160NB45A) at ambient and cryogenic conditions are reported. Compared to the wire-bond IGBT’s, press-pack IGBT’s are more suitable for cryogenic conditions as they do not have bonded connections and use fewer materials types, which reduces the risk of coefficient of thermal expansion (CTE) mismatch. The study has been conducted with a cryogenic testbed that provides a condensation-free condition during and after tests, which is essential for the preservation of the physical properties of IGBT’s being tested. The dynamic performance characterization results show that the switching speeds of both turn-on and turn-off are improved with substantially reduced tail current and increased dv/dt at cryogenic conditions. Moreover, the static performance characterization results show a reduction in collector-emitter voltage drop, indicating higher conductivity of the IGBT at cryogenic conditions. Furthermore, the impact of clamping force and gate lead length on the press-pack IGBT’s dynamic characteristics is reported. The findings of this study suggest that press-pack IGBT modules are suitable for cryogenic operation.

1. Introduction

One of the promising candidate technologies that is essential for the materialization of high-power-density power systems for future aircraft and shipboard applications is the superconductor technology. While superconducting cables [1,2], motors [3], generators [4,5], dielectric media and refrigeration systems have been researched extensively and are well understood [6–11], utilizing power electronics devices at cryogenic conditions is yet an existing challenge [12]. Power semiconductors, capacitors, and inductors are the key current-carrying components constituting any power electronics. The main challenge associated with operating these devices at cryogenic conditions originates from the mismatch of the coefficient of thermal expansion (CTE) among various materials comprising the devices [13]. Wire-bond IGBT modules, which are usually filled with gel, are prone to delamination at cryogenic conditions [14]. Electrolytic capacitors have no chance of surviving cryogenic conditions as the main charge carriers are ions, which will completely freeze. Inductors for cryogenic use will have to be designed to not have magnetic cores as eddy current loss will become substantial at cryogenic temperatures [15]. One of the ways of avoiding all of these challenges is by operating the power converter at ambient conditions while the rest of the system components are operated at cryogenic conditions. Since such solution is not ideal for maximizing the overall system efficiency, cryogenic compatible power electronics devices need to be developed for the materialization of a fully cryogenically operating power system that provides maximum thermal and system efficiency. The
efficiency enhancement is achieved by eliminating the current flow between cryogenic and ambient sections by operating all components in the cryogenic system. That is, significant amount of thermal loss at the cryogenic to ambient joints will be eliminated by operating all devices in a single cryogenic cooling loop. In addition to the enhanced system efficiency gained by reducing the cooling cost, the performance of the IGBT’s are expected to be enhanced at cryogenic conditions. Furthermore, the cryogenic operation provides the possibility of replacing the conventional conductors with thinner ones or with superconductors.

In this study, we focus on the cryogenic performance of press-pack IGBT modules. Although press-pack IGBT’s are not originally designed for cryogenic use, press-pack modules have the most cryogenically compatible design among IGBT packaging technologies given the simplicity of their design and the lowest variety of materials comprising the devices. With a long term plan of modifying existing technologies and developing cryogenically compatible IGBT modules, we investigated the cryogenic performance of an off-the-shelf press-pack IGBT technology.

![Figure 1. Cryogenic testbed used for characterizing the dynamic and static performance of the press-pack IGBT. (a) Double pulse test circuit [12], (b) Static test circuit [12], (c) Ambient section, (d) Press-pack IGBT and inductor, (e) Cryogenic section being filled with LN2.](image-url)
2. Experimental Setup

2.1. Cryogenic Testbed
For the dynamic and static characterization of the press-pack IGBT modules at cryogenic conditions, an experimental setup that consists of both cryogenic and ambient sections have been developed as shown in Figure 1. The cryogenic section is where the IGBT and the inductor are immersed in a bath of liquid nitrogen (LN\(_2\)). The ambient section is where the capacitor bank, microcontroller, and gate driver circuit are placed. For safety, we surrounded the ambient section with electrically grounded stainless-steel sheets, on which the control signal and the measurement terminals are mounted. The cryogenic and ambient sections are electrically connected by three conductor rods that are connected to the DC-link capacitors and the stack of IGBT modules. The three rods were fastened to a custom design nylon bushing mounted on the bottom plate of the ambient section via collar clamps, and the IGBT and the inductor were connected at the bottom of the rods. We mounted a large stainless-steel sink on a movable cart and thermally insulated the stainless steel container by covering it with foam boards. We used foam board adhesives to attach the boards on the stainless steel surface but also wrapped the foam boards with an elastic band to compensate for the possible loss of adhesion of the glue on cryogenic surfaces. Except for the stainless steel LN\(_2\) container, all parts were mounted on the top ambient section, which also functioned as a lid.

2.2. Modification of the IGBT Module
For conventional applications, press-pack IGBTs are hermetically sealed and filled with a dielectric gas to deal with the high electric fields at the IGBT and diode die edge terminations. However, these gases would be incompatible with cryogenic conditions as they condense at low temperatures. Therefore, for the cryogenic experiments, the top plates of the IGBT devices were opened such that LN\(_2\) could be filled as in Figure 2 (b). In this case, LN\(_2\) serves as a dielectric medium, but also as a cooling medium for the chips. Replacing the dielectric gas with LN\(_2\) does not pose significant impact in terms of dielectric strength nor in terms of cooling efficiency since LN\(_2\) is both a good dielectric and cooling medium.

![Figure 2. Press-pack IGBT structure [16]. (a) Cassette structure: many of these are installed in parallel in IGBT modules, (b) IGBT module: numerous cassettes are installed in parallel, the top plate was opened to displace the dielectric gas with liquid nitrogen.](image-url)
2.3. Preventing Thermal Shock
The cooling process of a test subject should not be too fast. Rapid cooling such as dipping the test subject into a bath of LN2 can lead to uneven thermal expansion/contraction within a device, which can generate substantial mechanical stress sufficient enough to permanently damage the device. Figure 3 shows a damaged IGBT die due to cold shock. The damage occurred when the press-pack IGBT module was immersed into a bath of prefilled LN2. Initially, the device blocked the DC-link voltage of 300 V, but became short circuited when the gate signal of 15 V was applied. The phenomena suggest that the device was exposed to a thermal shock that cracked and weakened the semiconductor die, which were completely punctured during the first few turn on and off process. To prevent damage caused by thermal shock, the press-pack IGBT modules should be placed in the cryogenic container first, and then LN2 should be filled gradually from the bottom of the container. Note that the level of precaution for the cooling process would vary depending on the test subject. In the envisioned applications where the power electronics would be operated in a cryostat, the devices would be cooled down progressively with no risk of cold shock.

![Figure 3. Photo of a damaged IGBT die due to cold shock. The cracks occurred during a rapid cooling process, and the press-pack IGBT module failed short when 15 V gate signal was applied with the DC-link voltage of 300 V. (a) Emitter side damage, (b) Collector side damage.](image)

2.4. Preventing Condensation
Preventing condensation is significant for maintaining the original physical properties of IGBT’s over numerous iterations of cryogenic tests and experiments. In our earlier experiments, we have observed condensation of the IGBT modules deteriorating the performance of the IGBT’s over many iterations of cryogenic tests. Figure 4 is a photo taken from the side of an IGBT cassette. A thick molybdenum platelet, which has a similar CTE value with silicon, is stacked on top of an IGBT die. As shown in Figure 4 (a), condensation generates whiskers on the molybdenum layer and causes damage at the interface of the IGBT die. To prevent condensation, we have equipped our new testbed with additional gas fittings that are used for filling the cryogenic section of the testbed with gaseous nitrogen while LN2 is being drained. The cryogenic section is kept mildly pressurized above ambient pressure with nitrogen gas to prevent air from leaking into the system. The new measure has been proven to be effective for preventing condensation, and we have been able to conduct multiple iterations of cryogenic tests without noticeable performance degradations.
Figure 4. Corroded IGBT cassettes due to condensation. This picture was taken from the side of the cassette after multiple iterations of cryogenic tests without properly executing the condensation prevention procedure. Whiskers formed on molybdenum plates. Silver layer detached from the IGBT die. (a) After corrosion. (b) Before corrosion.

3. Experimental Results

3.1. Dynamic Performance

The dynamic performance of a 4.5 kV, 160 A rated press-pack IGBT with anti-parallel diode (T0160NB45A) is assessed by measuring the switching voltage and current waveforms following a standard double pulse test procedure. Figure 1 (a) is the circuit diagram of a double pulse test experiment. The DC-link electrolytic capacitors, $C_{dc}$, providing the bulk of the energy to the pulse, are supplemented by a film capacitor, $C_{bypass}$, of lower parasitic inductance and resistance to offer a low impedance path to the switching currents from the stack. In this configuration, both the bottom IGBT module, and the top IGBT module’s anti-parallel diode, are being tested although the focus of this paper will be on the behavior of the bottom IGBT. The gate of the top module IGBT is shorted to avoid spurious turn on of the switch while the gate of the bottom module IGBT is driven between -10 – 15 V through a commercial gate driver and microcontroller. The inductor $L_{load}$ is first pre-charged to the target load current $I_{load}$ by turning on the IGBT for a duration $t_{precharge}$, fixed by the DC-link voltage $V_{dc}$ and the load inductance $L_{load}$ as follows:

$$t_{precharge} = \frac{L_{load}I_{target}}{V_{dc}}$$

At the end of the pre-charge, the IGBT is switched off and the load current freewheels through the anti-parallel diode of the top IGBT. The lower IGBT under test is subsequently turned on and off under the target load current and DC-link voltage and the corresponding switching waveforms are recorded to analyze the dynamic switching characteristics of the power device under test. The collector-emitter voltage of the IGBT under test is measured by a high-voltage differential probe connected to the bushing while the collector current is measured via a high precision shunt resistor inserted in the current path at room temperature.
Figures 5 and 6 are the voltage and current switching waveforms of the press-pack IGBT module. In both figures, the solid lines represent the measurements taken in LN$_2$ while the broken lines represent those taken at room temperature. Since the IGBT modules were opened to release the dielectric gas for the cryogenic experiments, we set the DC-link voltage for the double pulse test no higher than 1.5 kV to prevent unwanted dielectric failures. It should be noted that the voltage limitation of 1.5 kV was taken to ensure safety during the room temperature test, in which atmospheric pressure air is the dielectric media instead of the dielectric gas. In fact, we could have tested the device with higher DC-link voltage levels in LN$_2$, which is a good dielectric media, but stopped at 1.5 kV for a one-on-one comparison with the room temperature measurements. The standardized switching metrics [17] that are the current rise time at turn-on and fall time at turn-off, $t_r$ and $t_f$, respectively, are averaged for the different tests at room temperature and in LN$_2$ and summarized in Table I. The average $dv/dt$ at turn-on and turn-off are also provided, along with the average percentage change of the metrics at 77 K with the respect to the results at room temperature.

**Table 1. Average switching metrics of the IGBT at Ambient and Cryogenic.**

| Condition    | Average $dv/dt$ Turn-on [V/μs] | Average $dv/dt$ Turn-off [V/μs] | Average $t_r$ Turn-on [μs] | Average $t_f$ Turn-off [μs] |
|--------------|--------------------------------|---------------------------------|-----------------------------|-----------------------------|
| Ambient (293 K) | -558                           | 1670                            | 0.67                        | 1.21                        |
| Cryogenic (77 K) | -783                           | 2614                            | 0.68                        | 0.15                        |
| % Change at 77 K | 40.5 %                         | 56.6 %                          | 1.5 %                       | -87.6 %                     |

Figure 5 shows higher magnitudes of $dv/dt$ at both turn on and turn off in LN$_2$. The turn-on voltage waveforms, Figure 5 (b) are of particular interest, with a sharp voltage drop, until ~40% of the nominal DC-link voltage, followed by a lower $dv/dt$ phase at lower voltages, identical to the switching at room temperature. These higher $dv/dt$ are confirmed by Table 1 with an average $dv/dt$ 40.5% and 56.6% higher at turn-on and turn-off, respectively, at 77 K. The $dv/dt$ are lower at turn-on because of the configuration of the gate driver turn on channel following the standard practice to slow down the turn on of the IGBT to reduce the reverse recovery current from the opposite diode. The current waveforms at turn off shown in Figure 6 (c) demonstrates that the tail current is dramatically reduced at 77 K, owing to a higher recombination rate (i.e., shorter carrier lifetime) of the carriers at cryogenic temperature [18–20]. This lead to a much faster fall time in LN$_2$ than at room temperature, with an average $t_f$ reduced by as much as 87.6% as in Table I. The impact on the current rise time $t_r$, however, seems to be very limited with very similar $t_r$ in both cases. Further, the current waveforms at turn on, Figure 6 (b), show reduced reverse recovery currents from the antiparallel diodes at cryogenic temperature. This suggests that the Si diode also demonstrates better switching characteristics in LN$_2$, mostly because of reduced stored charges [18]. Finally, both voltage and current waveforms show that the turn-on process is delayed at 77 K, but the turn-off process occurs earlier than at room temperature. The phenomena are mainly caused by the increased threshold voltage of the press-pack IGBT at 77 K. This increase in the threshold voltage is mostly due to carrier freeze-out at cryogenic temperatures, as for any FET-based device [20,21]. This gives a better immunity to the common spurious turn-on in half-bridge configurations [22] and would potentially allow for a unipolar driving of the gate. The larger current magnitude at 77 K shown in Figure 6 (a) is mainly caused by the increased conductivity of the inductor which was also immersed in LN$_2$. 


Figure 5. Double pulse test results: voltage waveforms of the press-pack IGBT module at cryogenic and ambient conditions. (a) Turn-on and off waveform, (b) Close up view of turn-on, (c) Close up view of turn-off

Figure 6. Double pulse test results: current waveforms of the press-pack IGBT module at cryogenic and ambient conditions. (a) Turn-on and off waveform, (b) Close up view of turn-on, (c) Close up view of turn-off
It is apparent that the IGBT not only operates normally at 77 K but also demonstrates faster switching dynamics than at room temperature, as shown from both the voltage and current waveforms in Figures 5 and 6, and the average switching metrics of Table I. The results suggest tremendous advantages for the cryogenic operation of power electronics as faster switching results in lower switching losses, and potentially allows for an increase in the switching frequency of the converter, and in turn a reduction in the size of the passive elements ($L$ and $C$).

3.2. Static Performance

The static performances of the IGBT under test are assessed by measuring the collector-emitter saturation voltage $V_{ce(sat)}$ for different collector current $I_c$ using the test circuit shown in Figure 1 (b). As shown in Figure 7 (a), $V_{ce(sat)}$ increases with higher collector current $I_c$ both at room temperature and 77 K. While $V_{ce}$ at room temperature is lower than that at 77 K when $I_c$ is below 50 A, $V_{ce}$ at room temperature continues to increase more rapidly than $V_{ce}$ at 77 K when $I_c$ is above 50 A. This is due to the IGBT’s intrinsic structure and two conflicting phenomena observed at cryogenic conditions [19,21].

(i) Carrier freeze-out at cryogenic temperatures increases threshold voltage in the intrinsic PN junction region of the IGBT. This results in an increased knee-forward voltage in the $I_c$ vs $V_{ce(sat)}$ characteristic of the device.

(ii) A large increase of the carrier mobility in the inversion layer of the IGBT at cryogenic conditions lead to much higher conductivity modulation in this region.

The total collector-emitter saturation voltage of the IGBT is the sum of the voltage drops across the two aforementioned regions. At 77 K and low collector currents (< 50 A), effect (i) is predominant and leads to the observed higher $V_{ce(sat)}$ than at room temperature. For higher collector currents (> 50 A), effect (ii) is dominant than (i) and lower $V_{ce(sat)}$ values are observed at 77 K than at RT [21]. As $I_c$ keeps increasing, the reduction in $V_{ce(sat)}$ at 77 K becomes increasingly dominant. This is a significant finding showing that the current caliber of IGBT might be significantly increased at cryogenic temperature, as much as 50 % for the present device, for the same die area.

Figure 7 (b) shows decreasing $V_{ce}$ values with increasing gate voltage $V_{ge}$. When the room temperature data are compared with those measured in LN2, gate threshold voltage at 77 K is higher mainly due to carrier freeze-out.

![Figure 7](image_url)

Figure 7. Static performance test results. (a) $V_{ce}$ as a function of $I_c$, (b) $V_{ce}$ as a function of $V_{ge}$. 
3.3. Impact of Clamping Force
The electrical connection of press-pack IGBT modules are formed by clamping mechanisms. Proper clamping force must be maintained throughout the lifetime of press-pack IGBT modules to ensure device performance. In this section, we discuss the impact of loose clamping force on press-pack IGBT modules as clamping force may be changed at cryogenic conditions due to thermal contraction. For the study, we manually adjusted the clamping force of the press-pack IGBT. Due to the lack of a clamping force measurement system, we only performed the double pulse test under tight and loose clamping force conditions. In this section, we decided to focus on the turn-off current waveform because it showed the most pronounced effect of the clamping force among other sections of the current and voltage waveform. As Figure 8 shows, the strength of clamping force has an impact on the switching performance of the IGBT. Low clamping force resulted in a substantial amount of current resonance during turn-off. As we tightened the clamp, the resonance reduced. Depending of the type of the clamping mechanism and the material that consists the clamping system, such reduction in the clamping force at cryogenic conditions may occur in various magnitudes, and pose a negative effect on the switching performance of IGBT’s. It should be noted that the results shown in Figure 8 were obtained at room temperature to simply show the impact of clamping force on the switching performance of the press-pack IGBT. Hence, further study is necessary for the exact explanation on the clamping force variation and its impact on switching performance at cryogenic conditions.

![Figure 8](image)

**Figure 8.** Impact of clamping force on the current turn-off characteristics. The measurements were taken at room temperature with a DC-link voltage of 600 V.

3.4. Short vs. Long Gate Lead
In an actual power application, long gate signal leads may be required if the control board and the gate drive board are located far away from the IGBT modules. The distance is likely to be longer in cryogenic power applications as there are ambient and cryogenic sections in the systems. Therefore, in this section, we discuss the impact of gate lead length on the gate signal reaching the IGBT side because the parasitic resistance and inductance of the gate lead could distort the gate signal when a long gate lead is used. Figure 9 shows the experimental results obtained from two twisted gate leads of different lengths. Figures 9 (a) and (b) show voltage at the gate driver output and that across the gate and emitter of the IGBT. As shown in the figures, the voltage across the gate and emitter of the IGBT is slightly lower in the case of the 101-inch-long gate lead. The difference is mainly attributed to the higher resistance in the longer lead. Although the impact of the gate lead length seems insignificant, even longer gate leads need to be tested to draw a clearer conclusion.
Figure 9. Gate voltage waveform comparison between the gate driver side and the IGBT side. (a) 24 inch (0.61 m) gate lead, (b) 101 inch (2.56 m) gate lead.

4. Conclusions

In this paper, we investigated the cryogenic compatibility and the electrical performance of a press-pack IGBT module. Dynamic and static performance, the impact of cold shock, corrosion caused by condensation, and the impact of clamping force and gate lead length on the electrical performance of the IGBT device were discussed. Both dynamic and static electrical performances were enhanced at cryogenic conditions, and the potential mechanical and thermal challenges were partially addressed. The findings of this study show promise for the successful development of cryogenic power electronics devices as well as the materialization of a fully-cryogenically operating power system.

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