Cryogenic power electronics at megawatt-scale using a new type of press-pack IGBT

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Abstract. Electrical characteristics of a press-pack IGBT stack have been investigated experimentally in both static and dynamic tests at room temperature and at 77 K in an effort to identify a megawatt-scale class semiconductor that performs well electrically, thermally, and mechanically. It has been observed that the forward voltage drop and the turn-off time are both noticeably reduced at cryogenic temperatures, suggesting significant improvement in the device operating area. Furthermore, the stack was subjected to repeated thermal cycles between room temperature and 77 K without observing any degradation. A circuit simulation of a 200-kW boost converter based on the characterized press-back IGBT stack exhibited a reduction in switching and conduction losses at 77 K by 60\% and 24\%, respectively compared to the values at room temperature. It is expected that the type of press-pack IGBT stacks tested will be key elements to build high power dense, megawatt-scale cryogenic converters for future all-electric ships and electric airplanes.

1. Introduction
It may appear counterintuitive to operate a device that produces large amounts of heat, such as power electronic devices (PEDs), at cryogenic temperatures. The motivation behind developing cryogenic PEDs is to increase the power density, system wide efficiency, and enhance the reliability of the PEDs. The electric power distribution system on future all-electric ships and aircrafts is expected to operate at cryogenic temperatures to allow the use of high power dense superconducting motors, generators, and cables [1, 2]. For efficiency reasons, the power distribution system is likely to be based on medium voltage direct current (MVDC) topology. PEDs are required between AC devices like generators and motors and the DC bus (Fig. 1 (a)). The traditional warm PEDs would introduce a substantial heat load to the cryogenic system and require specialized interface components between the conductors at cryogenic temperature and the conductors at room temperature (RT) [3].
A closed loop cryogenic cooling system with a centrally located cryorefrigerator would be the most versatile and efficient system to serve multiple devices with diverse cryogenic operating temperatures of 30-70 K. In such a system, lowest temperature cryogenic fluid will probably be tapped for devices that benefit from operating at lowest possible temperatures. High temperature superconducting (HTS) generators and motors are examples of devices that are likely to operate at the low end of the available temperature window. HTS cables possess substantial power densities even in the warm end of the temperature window of 70 K. Based on specific application and system design, it might still be beneficial to operate HTS cables at 50-60 K to reap the benefits of high power densities or to reduce the amount of superconductor needed. (50 K in Fig. 1(b)). The cable terminations that serve as interfaces between the cable and the rest of the power system typically have a significant temperature gradient from the cable operating temperature of 50 K to the outer end of the current lead/bushing as high as 80 K. This would allow the PEDs that are in between the HTS cable system and the other devices to operate at 80 K. Since there is no liquid cryogen with such a temperature range, the proposed cooling loop would need to be based on helium gas, hydrogen gas, or sealed liquid nitrogen bath that is conductively cooled by the circulation loop.

Operating PEDs at cryogenic temperature can have other advantages besides reducing the heat influx into the cryogenic system: The reduction of losses of many of the components in the PEDs, the high heat transfer capabilities, and the high dielectric strength of the cryogenic fluid are expected to substantially increase the power density. Furthermore, the lower component temperature and reduced temperature cycles are expected to further increase the reliability [4].

In certain applications such as electric aircraft, the cryogen could also act as the fuel [2]. In such a case, the system could be operated as “open-loop” with the liquid cryogenic fuel (e.g. liquid hydrogen, liquid methane, or liquid natural gas) being pumped from the fuel tank to the power system devices and from there to the gas turbines or fuel cells.

![Fig. 1: Block diagram showing the power electronic devices between a HTS generator and a HTS motor (a) and the temperature profile of a proposed cryogenic cooling loop (b).](image-url)

2. Power Electronic Components at Cryogenic Temperature

The power electronic components of PEDs include semiconductors, capacitors, inductors, transformers, resistors, and varistors. Other components, which are not in the high power path, are not discussed here since they are considered to stay at room temperature (RT). These include the controller, parts of the current and voltage transducers, as well as the gate drivers. Current transducers might be based on transformer principle (AC only) or compensation current probes like Rogowski coils or Hall probe based transducers (mixed AC-DC) with a cryogenic primary and a RT secondary. The design of the converter will include a well-insulated cryogenic section (cryostat) and a RT section.

2.1. Semiconductors

Power semiconductors are at the heart of any power electronic converter and their operation and characterization at cryogenic temperatures have been the main focus of the ongoing research effort on cryogenic power electronics for the past 20 years [3]. In general, many silicon-based power devices
show significant static and dynamic performance improvements at cryogenic temperatures, along with an increased reliability due to lower junction temperatures and an increased integration density thanks to the higher thermal conductivity of packaging material and silicon. The reduced heat capacity at cryogenic temperatures will need to be taken into account, though.

Bipolar controllable devices such as power bipolar junction transistors (BJTs) and thyristors have been among the first power devices to be studied at cryogenic temperature. Thanks to the reduced carrier lifetime at cryogenic temperatures, an order of magnitude reduction in the turn-off time with a decrease in temperature from 300 K to 77 K has been reported for power BJTs [5]. An increase in the open base collector-emitter breakdown voltage by about 20% has also been observed. However, because of a reduced emitter injection efficiency and a decreased electron diffusion length in the base, a large reduction in the current gain by more than an order of magnitude is observed at cryogenic temperatures, which causes a serious problem in controlling these devices. Furthermore, a slight increase in the forward voltage drop is observed because of carrier freeze-out and increased emitter current crowding. Although an optimization of the BJT structure would be possible to overcome the current gain limitation at cryogenic temperatures as proposed by Singh et al. [5], the operation of commercially available power bipolar devices at these temperatures is not practical.

Field effect transistors such as MOSFETs do not suffer from the reduced controllability at cryogenic temperatures and display a lower on-state voltage drop and better switching characteristics [6–8]. However, the currently available voltage and current ratings in commercial devices do not meet the power level requirements of the envisioned applications that could benefit from power converters operating at cryogenic temperatures. Initial experiments with silicon carbide (SiC) based devices, which are expected to enable higher voltage and power ratings than their silicon counterparts, did not perform well at cryogenic temperature [9]. On the contrary, emerging AlGaN/GaN HFETs are promising for high power cryogenic applications and will need to be considered for detailed studied as they become commercially available [10].

IGBTs rely on the same control principle as FETs, therefore offering full controllability at cryogenic temperatures, are available in the medium power range with devices rated up to 6.5 kV and 3 kA, and as such constitute the most promising candidate for the target applications. Several studies [11–15] have shown a large reduction in the tail current owing to reduced carrier lifetime at cryogenic temperatures, which could be a motivation to increase the switching frequency and/or the current rating. A decrease of the on-state voltage has also been observed thanks to the large increase in the inversion layer carrier mobility that overbalances the increase of the knee forward voltage intrinsic PN junction due to carrier freeze-out. As for any FET device, an increase in the gate threshold voltage due to carrier freeze out at lower temperature has been reported [11–15].

Although low power IGBT devices have been extensively studied, no experimental results on medium power IGBTs are available. Furthermore, very little attention has been paid to the device packaging and the mechanical constraints arising from the coefficient of thermal expansion (CTE) mismatch of materials, potentially damaging the device during the thermal cycles. In a conventional power module, several potential weaknesses for cryogenic operation, including repeated thermal cycling between room temperature and cryogenic temperatures, can be anticipated: the solder joints between the chips and substrates; the joint between the substrates and the baseplate; the busbar connections to the substrates (soldered or welded); the interface between the gel (or other potting materials) and the chip termination coatings; and, maybe most critical, the interaction of the gel (and other potting materials) with the wire bonds. Most promising instead seem to be pure pressure contact devices with packages that are based on metals and ceramics only, and which construction avoids soldered joints, wire bonds and gel potting altogether. Press-pack devices such as high power diodes and thyristors fall into this category. However, only recently a manufacturer (IXYS UK Westcode) started packaging IGBTs in traditional press-pack modules for megawatt-scale, high reliability applications [16, 17]. These devices combine the most suitable semiconductor type with the most suitable package, making them a good choice for megawatt-scale cryogenic power applications.
2.2. Inductors and Transformers

The design of power electronic devices typically include inductors and sometimes transformers. These typically consist of copper or aluminum windings on a magnetically soft core. The core increases the inductance of the inductors and improves the coupling between the windings in transformers. An ideal core has high magnetic permeability over the desired frequency range, a high saturation flux density, low hysteresis, and low electric conductivity. The low conductivity is important to minimize eddy currents that cause losses in the core.

There are two common materials used for the core: laminated transformer steel and compacted metal powder. Laminated steel cores are common in high power devices, which typically operate at switching frequencies below 15 kHz. Modern grain oriented silicon steel is an anisotropic material, which offers high permeability at comparatively low electrical conductivity. In certain designs, they incorporate an air gap, which avoids core saturation in certain types of converters such as flyback converters, which use the core to store energy between switching cycles. Powder cores are more often used in lower power devices, which operate at higher switching frequencies typically above 100 kHz. Powder cores offer high magnetic permeability, a so-called distributed air gap, and low conductivity, minimizing eddy currents without the need for lamination. There is a wide range of sintered magnetic materials used for the fabrication of powder cores including iron, carbonyl iron, nickel-iron, and molypermalloy.

Neither of these core types are expected to be suitable for cryogenic use. Transformer steel shows a substantial increase in conductivity, increasing eddy currents and core losses. No literature could be found on voluminous powder cores at cryogenic temperature but the authors would expect them to exhibit issues with material embrittlement and eventually cracking. The development of new core materials for cryogenic use might be a valuable research task.

Two solutions are proposed:
1. Keep the core at RT and operate only the winding(s) at cryogenic temperatures. This requires a non-magnetic cryostat that insulates the cold winding(s) from the warm core.
2. Design of core-less ("air core") inductors and transformers. This might result in substantially more voluminous solutions. However, the higher permissible current density in the copper or aluminum windings operating at cryogenic temperatures might compensate partially for the increase in volume. The current density could potentially be further increased if superconducting windings would be used.

2.3. Capacitors and Varistors

Capacitors and varistors are problematic to operate at cryogenic temperature. There are several different capacitor technologies, typically named after the dielectric material. The dominating technology for large size DC link capacitors is electrolytic, which does not operate at temperatures below the freezing point of the electrolyte. Other technologies include polymer film capacitors, ceramic capacitors, tantalum and niobium capacitors, and vacuum capacitors. As the temperature drops, the metallized layers/foils as well as the polymer foil shrinks according to their respective material properties (CTE). A mismatch in CTE can lead to delamination and damage of the capacitor. There are some reports of encouraging results of capacitors at cryogenic temperature [18–20]. However, these studies focused on small volume capacitors only. It is expected that the mismatch in CTE becomes a bigger problem for larger size capacitors.

Two solutions are currently being investigated: The use of capacitors at RT as well as focusing exclusively on converter technologies that work without large size capacitors such as current source converters and direct converters, for instance matrix converters. However, even those topologies typically require (smaller) capacitors in the filter and snubber circuits.

Varistors share the difficulties that capacitors have with the large interface area between two materials of dissimilar CTE. However, since they are expected to absorb surge energy by turning it into heat, varistors also suffer from the reduced heat capacity of solid materials at cryogenic temperatures [21].
2.4. Interconnects

Power electronic devices need to interconnect semiconductors, capacitors, inductors, current sensors, voltage sensors, and circuit breakers in a way that is most compact and often at lowest inductance. This is typically achieved by bus plates that are stacked and insulated against each other by plates often made of glass-fiber reinforced resins. The bus plates are typically made of copper or aluminum. The resistivity of these materials drop substantially at cryogenic temperature, reducing the losses and/or reduce the necessary plate thickness. The resistivity of (pure) aluminum and copper are comparable at $4.96 \times 10^{-16} \Omega \cdot m$ and $5.01 \times 10^{-16} \Omega \cdot m$, respectively at 50 K so that using the lighter aluminum could be an attractive solution [22]. At temperatures below approximately 50 K, aluminum features a higher conductivity than copper. However, the typically increased contact resistance of aluminum needs to be taken into account and might require electroplating of the interconnects. It might also be possible to develop superconducting interconnects to further increase the power density and efficiency.

2.5. Cryogenic Media

There are both liquid and gaseous cryogenic media that would be suitable for PEDs. Liquid media generally have the advantage of higher dielectric strength and improved heat transfer, which would allow to increase the volumetric power density. In case of a liquid cryogenic medium, the losses in the PED will evaporate some of the liquid cryogen. This mass flow rate $\dot{m}_{\text{evap}}$ formed can be calculated:

$$\dot{m}_{\text{evap}} = \frac{P_{\text{Loss}}}{\Delta H_{\text{vap}}} \quad (1)$$

where, $P_{\text{Loss}}$ are the losses in the converter and $\Delta H_{\text{vap}}$ is latent heat of vaporization of the cryogen, which is approximately 199.2 J/g and 510.8 J/g for LN$_2$ and LCH$_4$, respectively [23]. For each kilowatt of losses, 5.02 g/s of LN$_2$, or 1.96 g/s of LCH$_4$ would be evaporated. Depending on the application, the vapor can be condensed back into a liquid, used as a gaseous medium or fuel, or vented.

3. Static and Dynamic Characterization of a Press-Pack IGBT Stack in LN$_2$

3.1. Static Characterization

In an effort to identify a power semiconductor that performs well electrically, thermally, and mechanically and that could be used in a megawatt-scale class cryogenic power converter, a medium voltage IGBT stack from IXYS/WESTCODE has been characterized at 77K in LN$_2$. The stack of IGBTs consists of two identical IXYS T016NB45A modules, rated for 4500 V and 160 A (Fig. 2 upper left). The modules include an IGBT and an antiparallel diode as needed for voltage source converter applications. The series include models with ratings of up to 6500 V and up to 3000 A. All IGBTs of this series are of ceramic press-pack type, which is foreseen as the most promising packaging type for cryogenic applications. In this experiment, the top flange was ground off to allow LN$_2$ to flow into the package and cool the IGBT and diode dies. LN$_2$ also serves as the dielectric and provides sufficient dielectric strength well in excess of the electric fields expected in a 4500 V rated device. The stack does not include dedicated heatsinks. However, the leads consisting of copper plates are designed to help dissipate the heat generated.

Only one of the two IGBTs was used for the static experiment. A 5 V and 900 A rated DC power supply was used in current control mode to provide a current of up to 160 A. Since the stack did not include any particular measures for thermal control (heat sinks etc.), each test was only conducted for a few seconds to avoid excessive heating. The gate voltage was provided by a second power supply, set to voltages of $V_G = \{11, 13, 15, 17, 20\} \text{ V}$. For each of the gate voltages, the $V_{CE}$ voltage drop was measured. The experiment was repeated in ambient air at room temperature. The results indicated a substantial reduction of $V_{CE}$ at cryogenic temperature (Fig. 3). This could result in a reduction of conduction losses of approximately 5-20%.
It should be noted that the actual operating temperatures will deviate from 77 K and RT respectively. For standard converter applications, the thermal design is typically designed to maintain a maximum temperature at full power substantially above RT but well below the rated junction temperature of 125°C. For cryogenic applications, the thermal design could either be optimized to operate at a temperature just slightly above the boiling point of the cryogen using its enthalpy of evaporation to maintain the temperature over a wide range of power. Alternatively, the temperature could be substantially above the boiling point, which would displace the liquid inside the package by gas. Under these conditions, both the heat transfer and dielectric strength would be reduced and would need to be carefully managed.

Fig. 2: Picture of the IGBT stack (top left), cart with integrated cryostat (top right), DC link and controller (bottom left), and filling the cryostat with LN$_2$ (bottom right)

A schematic of the test configuration is illustrated in Fig. 3 (a). Based on the test setup, the output characteristic ($I_C$-$V_{CE,sat}$ under a certain $V_G$) of the IGBT is obtained and summarized in Fig. 4. Except for the condition of $V_G = 11$ V, relative to the curves at RT, the “knees” of the curves at 77 K shift to higher voltages, while the slopes of the curves at 77 K increase. In other words, the shapes of the curves at 77 K and more “square”. Besides, except for the condition of $V_G = 11$ V, $V_{CE,sat}$ at RT is lower than that at RT if $I_C$ is higher than a certain threshold, while $V_{CE,sat}$ at 77 K is lower if $I_C$ is lower than the certain threshold. The threshold voltage increases with $V_G$. The temperature-related variation is due to two factors: fewer free carriers and higher carrier mobility at cryogenic temperatures. A decrease of the on-state voltage has also been observed thanks to the large increase in the inversion layer carrier mobility that overbalances the increase of the knee forward voltage intrinsic PN junction due to carrier freeze-out [12]. The variation of output characteristics could result in a reduction of conduction losses of 5-20% if $I_C$ is larger than 50 A, as illustrated in Fig. 5.
Fig. 3: Test configurations used to for static characteristics (a) and the double pulse test (b).

Fig. 4: Output characteristics of the IGBT at RT and 77 K (a) and $\Delta V_{CE,sat}/\Delta I_C$ of the linear part of $I_C-V_{CE,sat}$ curve (b).

Fig. 5: Variation of conduction loss of the IGBT at 77 K.

In addition, the output characteristic under $V_G = 11$ V presents a different trend from those under higher $V_G$. The curve for $V_G = 11$ V and 77 K deviates from others at about $I_C = 15$ A, which is significantly lower (about $I_C = 120$ A) under $V_G = 11$ V and RT. The phenomenon means that the threshold voltage $V_{G,th}$ of the IGBT at 77 K is higher than that at RT, which is caused by the lower number of free carriers at 77 K.

The $\Delta V_{CE(sat)}/\Delta I_C$ of linear part of $I_C-V_{CE(sat)}$ curve is provided in Fig. 4 (b), which shows that the relative on-state resistances of the IGBT under cryogenic temperature is much less than those under room temperature.

3.2. Dynamic Characterization

The same stack of IGBTs was characterized using the standardized double-pulse experiment (Fig. 3 (b)). The load inductor is connected across the top IGBT module and consists of 168 turns of 0.823 mm$^2$ magnet wire resulting in an inductance of 552 $\mu$H. The DC resistance is 0.4 $\Omega$ at RT and 57 m$\Omega$ at 77 K.
The DC link capacitor was kept outside the cryostat and at RT, which results in a total inductance of the main current path of 200 µH. The gate drivers were also operated at RT, which required 50 cm long twisted gate leads, slightly longer than the recommended maximum of 30 cm, yet extra precautions have been taken to avoid any gate resonance. The gate signal was generated in a microcontroller and consisted of the initial on pulse of 150 µs followed by the off pulse of 100 µs, followed by another on pulse of 30 µs followed by another off pulse. The resulting current, voltage, power loss, and gate signal are shown in Fig. 6.

Figure 6 compares the switching performance of the press-pack IGBT at RT and 77 K and shows an improvement of the turn-on dynamic and a reduction of the turn-off time of the IGBT. Figure 6(a) shows the current waveform of the IGBT during the double pulse test. During the turn-on process, the collector current $I_C$ shows a smaller overshoot, which is due to the reverse recovery current of the top anti-parallel diode, at 77 K than at RT. The smaller $I_C$ overshoot at 77 K is due to the anti-parallel diode storing a smaller amount of charge during conduction at lower temperature [24]. The higher on-state value of $I_C$ at 77 K is mainly due to the increased conductivity of the inductive load of the double pulse experiment. A noticeable improvement is observed in the turn-off performance of the IGBT. In this study, the $V_G$ of $-10$ V was used to turn off the device, and +15 V was used to turn on the device (Figure 6(d)). The negative $V_G$ quickly removes the inversion channel current and eliminates the base drive current. However, the bipolar transistor collector current decays slowly since the excess carriers are removed by recombination. Therefore, the IGBT turn-off current characteristics can be divided into two stages: a rapid decrease stage and a slowly decaying stage [24]. At turn-off, a larger initial drop in $I_C$ is followed by its gradual decay, commonly referred to as the tail current. The two-stage turn-off process was observed both at RT and 77 K (Figure 6 (a)). However, a comparatively faster initial current drop and shorter tail current was observed at 77 K. The faster turn-off is mainly due to lower transistor gain and the reduced lifetime of minority carriers at lower temperature [24]. Due to faster current decay, a higher turn-off voltage overshoot was observed at 77 K as shown in Figure 6 (b). The turn-off voltage overshoot is mainly caused by the induced voltage across the inductive load of the double pulse test setup. Figure 6 (b) also shows that the voltage reaches its steady state after the overshoot faster at 77 K than at RT, which corresponds to the shorter tail current of Figure 6 (a). Furthermore, Figure 6 (c) shows the switching power loss of the IGBT. As expected from the current and voltage waveforms, both the turn-on and turn-off switching energy loss is comparatively smaller at 77 K than at RT. Lower switching energy loss indicates lower thermal stress in the device and thus opens the possibility of operating the IGBT at a higher switching frequency at 77 K.

Based on the test results, the device is comparatively more efficient at 77 K, which was expected since similar findings have been reported in previous work on power semiconductors at cryogenic temperature [25]. The increase in efficiency in the semiconductors is potentially overcompensated by the additional effort to provide cooling at cryogenic temperature. However, the most important finding is that this IGBT stack has been cycled between RT and 77 K more than a dozen times without any degradation. This is new for devices fabricated in a fully industry compatible package.

3.3. Simulation Model of a 200-kW Boost Converter

Based on the encouraging results from the static and double pulse test, a 200-kW boost converter was modeled in PLECS. The input voltage was 1,500 V and the output voltage was 2,000 V. The input inductance was assumed to be 6.3 mH, the output capacitance was 140 µF, and the switching frequency was 2 kHz. The turn-on and turn-off characteristics of the IGBT module was taken from the characterization experiment. At RT, the switching and conduction losses in the IGBT were 373.2 W and 96.1 W respectively (total: 469.3 W). At 77 K, the losses were 147.6 W and 73.4 W respectively (total: 221.0 W). This corresponds to a reduction of losses in the IGBT by 53%. The losses in the inductor could be reduced by a factor of seven if the cross section of the wire is kept identical. Alternatively, the cross section could be reduced to reduce the volume and weight of the inductor.
Fig. 6: Collector current (a), collector-emitter voltage (b), power loss (c), and gate signal (d) during the double pulse test.

4. Conclusion
Several challenges exist with the design of cryogenic power electronic devices. This is especially true for applications at medium and high power levels. Semiconductors are the key components of power electronic devices and are the primary focus of this study. To the best of authors’ knowledge, this is the first time that a megawatt-class IGBT phase leg has been successfully characterized at cryogenic temperatures. The IGBT phase leg performed well in both static and dynamic tests. In a simulated boost converter configuration, the switching and conduction losses are reduced by 60% and 24%, respectively compared to the values at room temperature. The turn-off time is reduced considerably, potentially enabling higher switching frequencies. Repeated thermal cycles between room temperature and 77 K of the IGBT phase leg did not show any deterioration in performance. The next steps in this project will include characterization of the breakdown voltage at cryogenic temperature and characterizing of the diode. Based on the encouraging results, the authors are planning to design and build a converter based on the tested phase leg to further understand the intricacies of operating power electronics at cryogenic temperatures.

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