Power electronics performance in cryogenic environment: evaluation for use in HTS power devices

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Abstract. Power electronics (PE) plays a major role in electrical devices and systems, namely in electromechanical drives, in motor and generator controllers, and in power grids, including high-voltage DC (HVDC) power transmission. PE is also used in devices for the protection against grid disturbances, like voltage sags or power breakdowns. To cope with these disturbances, back-up energy storage devices are used, like uninterruptible power supplies (UPS) and flywheels. Some of these devices may use superconductivity. Commercial PE semiconductor devices (power diodes, power MOSFETs, IGBTs, power Darlington transistors and others) are rarely (or never) experimented for cryogenic temperatures, even when designed for military applications. This means that its integration with HTS power devices is usually done in the hot environment, raising several implementation restrictions. These reasons led to the natural desire of characterising PE under extreme conditions, e.g. at liquid nitrogen temperatures, for use in HTS devices. Some researchers expect that cryogenic temperatures may increase power electronics’ performance when compared with room-temperature operation, namely reducing conduction losses and switching time. Also the overall system efficiency may increase due to improved properties of semiconductor materials at low temperatures, reduced losses, and removal of dissipation elements. In this work, steady state operation of commercial PE semiconductors and devices were investigated at liquid nitrogen and room temperatures. Performances in cryogenic and room temperatures are compared. Results help to decide which environment is to be used for different power HTS applications.

1. Introduction

Power electronic devices are commonly used in energy systems. Since superconductor devices find many potential applications in energy systems, the study of power electronic devices at cryogenic temperature may be useful. The goal of power electronics investigation at cryogenic temperatures is to improve overall systems efficiency. At low temperatures, semiconductor materials are expected to have better electronic, electrical and thermal properties than at room temperature [1].

Improving a system efficiency, also depends of the right choose of electronic components used. For instance, the bipolar junction transistor (BJT) relies on thermal excitation to let conduction happen. In this way, BJT is expected to freeze out at cryogenic temperatures, having lower performance than at room temperature. On the other hand, MOSFET performance should increase at cryogenic temperatures, due to an increase in carrier mobility, a higher transconductance and a higher threshold

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voltage. In [2], it is theoretically demonstrated that the MOSFET gain is in the order of 20 to 45% greater in the region of 100 K than at room temperature. Also, for a MOSFET inverter circuit, the delay propagation decreases near to 65% for cryogenic temperature.

Another reason to study power electronics at cryogenic temperatures is aiming to provide higher power densities systems. In [3] a power MOSFET was simulated under room and cryogenic temperature using the device model adopted by Spice simulator. The simulation results showed that for this device current increases 3 times from 300 K to 77 K. The reason for current increase was the higher carrier and channel mobility at cryogenic temperatures, which leads to larger current density in the device.

Other device characteristics vary when temperature decreases. In [4], some experiments were made with a commercial high-voltage MOSFET. Results showed that on-resistance decreases by a factor of 10-20 or more depending on the drain current if cooled down at 77 K. Similar results were achieved by Shenai [5], when a low-voltage power MOSFET at liquid nitrogen was tested.

Switching and lower dynamic losses of power electronic devices was also verified at cryogenic temperatures. The static and dynamic behaviours of different power devices, as diode, IGBT and GTO, were simulated at lower temperatures in [6]. The experimental results for each device showed an improvement of switching and dynamic losses at liquid nitrogen, when compared with the room temperature ones.

Other experiments are reported in the literature, as in [7]-[9], where we can obtain experimental data concerning the performance of power electronic devices at cryogenic temperatures.

In this paper we will present the experimental results of commercial power electronic semiconductor devices at room and cryogenic temperature. The tested devices are power diode, bridge rectifier, power MOSFET and power Darlington transistor.

2. Experimental results
The aim of this work is to report the experimental results of commercial power electronic devices, when operating under cryogenic temperatures and its comparison with room temperature. Typically all datasheets for commercial devices just guarantee a good behaviour in the range -40 to 150 ºC. We tested four power electronic devices, a power diode (40EPS08 40A), a bridge rectifier (GBPC3504 35A), an N-channel MOSFET (STP16NF06 16A) and an NPN Darlington transistor (BDW93C 12A). All the devices were tested with a resistive load.

2.1. Power diode
The characteristic obtained by experimental procedures for the power diode, is represented in figure 1. As we can easily see, the diode presents two distinct curves for room and cryogenic temperatures. The characteristic at room temperature is in agreement with the datasheet. Under liquid nitrogen, the diode presents a similar curve, but higher forward voltage, about 40 % more than for room temperature. Equation (1) describes the diode characteristic, where $I_S$ is the reverse saturation current, $k$ a constant dependent on the material (Ge or Si), $V_D$ the forward voltage and $T_K$ the temperature.

$$I_D = I_S \left( \exp \left( k \frac{V_D}{T_K} \right) - 1 \right)$$

Admitting constant values for $I_S$ and $k$ we may easily conclude that to keep the same current through the diode, the ratio $V_D/T_K$ must be constant. Since the temperature decreases to cryogenics, the forward voltage should increase for the same carried value at room temperature.

2.2. Bridge Rectifier
In figure 2 the bridge rectifier characteristics obtained from experimental procedure are presented. In opposition to the diode experimental results, for room and liquid nitrogen temperatures, the bridge rectifier presents identical characteristics for the same current delivered to the load.
The justification used to explain why forward voltage increases for the diode at liquid nitrogen temperature should be the same for the bridge rectifier. In this way, we just can assume that the semiconductors didn’t cool down to 77 K, due to the device shell.

**Figure 1.** Diode Characteristic at room (blue) and liquid nitrogen (red) temperature.

**Figure 2.** Output Characteristic of a Bridge Rectifier at room (blue) and liquid nitrogen (read) temperature.

2.3. N-channel MOSFET

This work also explores the operating characteristics of a power MOSFET under cryogenic conditions. Some important results were already obtained by simulation using the semiconductor device model [3]. One of the results illustrates the drain current vs. drain voltage at 77 and 300 K, where is clear an increase in current by a factor of 3.5 at 77 K when compared to that at 300 K, for the same \( V_{DS} \) values.

The results presented in [3], are in agreement with theoretical results since if electron mobility increases the on-resistance decreases and transconductance increases, as expected. On the other hand, an increase in threshold voltage will occur.

Figure 3 illustrates the output characteristics at room temperature, obtained from datasheet, of the power MOSFET under testing. In figure 4 experimental results are showed. The drain current vs. drain voltage for a gate voltage of 5 and 6 V\(_{DC}\) at liquid nitrogen temperature are illustrated.

Our experimental results didn’t show relevant differences between room and liquid nitrogen temperature, device performance. We just had chance to test the power MOSFET for a restrict operation region, but for the same operation region, some references shows different performance at room and cryogenic temperatures. Once again, the temperature inside the device should not be as lower as we intended.

**Figure 3.** Mosfet output characteristics, at room temperature obtained from datasheet.

**Figure 4.** Mosfet output characteristics, at liquid nitrogen temperature obtained from experiments.
2.4. NPN Darlington Transistor

The last practical test was made to a power NPN Darlington transistor. Figures 5 and 6 illustrate the characteristic collector current vs. collector voltage for a base current of 15 and 20 mA, respectively. Analysing both figures, a better performance of the device at room temperature than at liquid nitrogen temperature is observed. For the saturation region and for the same current carried through the collector at cryogenic temperature, an increase of about 20% of the voltage drop is observed when compared with room temperature.

At liquid nitrogen temperature, the necessity of higher voltage and consequently more losses on the device, for carrying the same current than at room temperature, appears because BJT relies on thermal excitation to let conduction to occur. The power Darlington transistor characteristics, available in datasheet, confirm a better performance for higher temperatures.

![Bipolar NPN Characteristic (Ib = 15mA)](image1.png)

**Figure 5.** NPN Darlington transistor characteristic for $I_b = 15\text{mA}$ at room and liquid nitrogen temperatures.

![Bipolar NPN Characteristic (Ib = 20mA)](image2.png)

**Figure 6.** NPN Darlington transistor characteristic for $I_b = 20\text{mA}$ at room and liquid nitrogen temperatures.

3. Conclusions

It is a wrong idea to admit *a priori* that all devices operate significantly better at cryogenic temperature compared to room temperature. Operational and physical aspects must be taking into account when choosing a commercial device to operate at cryogenic temperature.

In this work, we presented four power commercial devices, which were tested at liquid nitrogen temperature. A variety of tests were performed and the results are presented. Performances in cryogenic and room temperature were compared. In two cases the experimental results agreed with those expected theoretically. With other two devices, we didn’t observed significant changes between cryogenic and room temperature performance.

As future work, a more exhaustive study will be done to this and other commercial devices. In this way, a better knowledge about physical phenomena can help to understand the device’s behaviour at cryogenic temperatures and decide whether or not to use it that way.

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