Cryogenic Power Electronics: Capacitors and Inductors

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Abstract. Capacitors and inductors that are suitable for cryogenic use are presented in this study. With the long-term goal of developing power electronic converters for cryogenic use, we studied various off-the-shelf metalized polypropylene film capacitors at cryogenic and ambient conditions. Capacitance and breakdown voltage of the film capacitors were the main parameters measured at room temperature and in liquid nitrogen. The results show that the material of dielectric film and the method of packaging play a role in the characteristics of breakdown voltage and capacitance in cryogenic conditions. In general, both capacitance and voltage rating of the capacitors were comparable if not better at cryogenic conditions. Moreover, with the long-term goal of developing inductors for cryogenic applications, we built and tested inductors with and without a magnetic core. The resistance, inductance, maximum current, and energy density were measured and compared. According to the results, the energy density of the cryogenic inductor without a magnetic core can be designed to be much higher than its room temperature counterpart mainly due to the superior cooling power of liquid nitrogen and the reduced resistivity of the windings at cryogenic temperatures.

1. Introduction

Superconducting technology is one of the promising candidate technologies that enables to build power systems of high power density, which is essential for future aircraft and shipboard applications. Superconducting cable, motor, and generator technologies have been demonstrated [1–4]. Also, the cryogenic dielectric and cooling media for these applications have been studied extensively [5–9]. However, developing power electronics devices suitable for cryogenic conditions is yet an existing challenge [10,11]. In particular, the experience with the development of cryogenic passive components is incomplete. The mismatch of the coefficient of thermal expansion (CTE) among various layers and parts of materials comprising passive components, and the increased eddy current loss of magnetic cores are the main challenges. Electrolytic capacitors fail to function at cryogenic conditions as the main charge carriers are ions, which are immobile due to the frozen electrolyte at such conditions. In addition, as eddy current loss in magnetic cores becomes substantial at cryogenic temperatures due to the enhanced conductivity of the material, cryogenic inductors will have to be designed either with warm cores or without cores at all. For the development of a fully cryogenically operating power system, which is expected to show substantially improved system efficiency and life expectancy, the successful development of cryogenically compatible passive components is essential.

In this study, we discuss the capacitor and inductor technologies. For the capacitors, we took several off-the-shelf metalized polypropylene film capacitors and tested them at both room temperature and at 77 K. We focused on observing the variation of capacitance and breakdown voltage as a function of temperature, dielectric film material, and packaging method. To understand the feasibility of developing cryogenic inductors without a magnetic core, we built and tested two prototype inductors; one with and one without a magnetic core.
2. Cryogenic Capacitor

We took several types of metallized film capacitors and tested in both ambient and cryogenic conditions. Electrolytic capacitors were not investigated as they do not work at low temperatures, at which ionic charge carriers freeze out. Capacitance and voltage withstand capabilities were measured at a room temperature and in a bath of liquid nitrogen as shown in figure 1. Initially, small-scale metallized film capacitors were tested with the test setup [11]. Capacitance was measured with an LCR meter and the voltage withstand capability was measured based on the self-healing process of metallized film capacitors that is achieved when current is limited while ramping up the voltage of the power supply [11]. The results showed increased capacitance and voltage withstand capabilities in liquid nitrogen. The increased capacitance can be attributed to the variation in permittivity and the shrinkage of the dielectric layers. As the results were promising, we decided to continue the investigation with larger film capacitors. Figure 1 (a) shows the KEMET C44HLGR6600AASJ film capacitor that was tested, and Figure 1 (b) shows the experimental setup used for the study.

The capacitance was measured with an LCR meter and the voltage was tested up to the voltage of 600 V. Safety concerns based on the large size of the capacitor prevented testing up to the breakdown voltage of the capacitor. The capacitor test results are shown in Table 1. Consistent with the small-scale capacitor test results of our previous study [11], the large film capacitor also showed increased capacitance and no sign of degradation in voltage withstand capability at cryogenic temperature.

![Figure 1](image.png)

**Figure 1.** Cryogenic testbed used for characterizing the capacitance and the withstand voltage of a polypropylene metallized film capacitor. (a) KEMET C44HLGR6600AASJ (600 μF, 700 Vdc), (b) Experimental setup.

| Condition       | Capacitance [μF] | Tested DC Voltage [V] |
|-----------------|------------------|-----------------------|
| Ambient (RT)    | 597              | 600                   |
| Cryogenic (LN$_2$) | 620              | 600                   |

Table 1. Cryogenic Capacitor Test Results Measured at 1 kHz.
3. Cryogenic Inductor
The main challenge in developing a feasible cryogenic inductor is not being able to use magnetic cores, which generates a substantial amount of loss due to increased eddy currents. The only ways to avoid such increased loss are (a) by designing cryogenic inductors without magnetic cores, which in turn compromises the achievable inductance of the inductor, or (b) keep the core warm, which adds complexity and reduces the power density. Nevertheless, there are several advantages of operating inductors in cryogenic conditions, which are the enhanced conductivity of the windings, increased cooling power provided by liquid nitrogen, lower mass, and higher dielectric strength. The reduced resistivity of the windings allows higher current densities. The substantial amount of heat transfer provided by liquid nitrogen keeps the resistivity of the windings low at high currents. The reduction in mass achieved by not using a magnetic core is essential for applications that require light weight. The higher dielectric strength provided by liquid nitrogen, which has a dielectric strength typically higher than 35 kV/mm [12] (i.e., more than an order of magnitude higher than air), allows cryogenic inductors to be operated at medium to high voltage power applications.

![Figure 2. Inductance comparison. (a) A total gap distance of 6.76 mm was obtained by inserting two 3.38 mm thick G10 plates between the upper and lower ferrite magnetic cores. The resulting inductance was 244 µH. (b) The inductance of the coreless inductor was 21.3 µH.](image)

3.1. Inductance: RT vs. 77 K
To understand the performance of a coreless cryogenic inductor, we wound a copper wire 27 times around a bobbin such that it can perform both as an ambient inductor with a magnetic core as well as a coreless cryogenic inductor. The inductors used for this study are shown in Figure 2. We used two U-shaped ferrite cores, separated with two 3.38 mm thick G10 (high-pressure fiberglass laminate) plates on each side. The measured inductance value of the inductor with the core was 244 µH at 1 kHz. On the other hand, the inductor without the magnetic core showed the inductance of 21.3 µH. The difference in inductance is mainly due to the existence of the magnetic core.

3.2. Dissipated Power, Resistance, and Energy Density: RT vs. 77 K
With the ultimate goal of measuring the energy density of the inductor at room temperature and 77 K, we conducted a maximum current experiment as shown in Figure 3. We used a high-current power supply that can output up to 900 A in current control mode. A shunt resistor was installed in series to measure the current more accurately that what could be read on the display of the power supply. The tested inductor, which was either placed at ambient or in a bath of LN₂, was connected through a copper braid to prevent excessive voltage drop in the lead. The voltage across the inductor and the shunt resistor was measured by a National Instruments Data Acquisition system (NI DAQ).
Figure 3. Testbed for measuring the maximum current limitation of the inductor.

The cryogenic test was conducted in an open bath of LN$_2$. The current was increased from 10 A with a 10 A increment as high as 240 A, at which point the inductor failed (contact between wire and current lead overheated and melted, shown in Figure 4(a)). The experiment at room temperature was conducted with the identical setup with the only difference of the inductor being placed at ambient. Current was increased from 10 A with a 5 A increment up to 55 A, at which the bobbin started to turn brown.

![Figure 4] Experimental results of the inductors. (a) Photo showing the location of the meltdown, (b) Measured dissipated power, (c) Measured resistance, (d) Measured energy density.
Based on the measured voltage and current values, dissipated power, resistance, and the energy density were calculated as shown in Figure 4 (b) – (d). Compared to the measurements taken at 77 K, measurements taken at room temperature commonly show a steeper increase. The dissipated power (Figure 4 (b)) and the measured resistance (Figure 4 (c)) increased faster at room temperature due to the higher resistance of the copper windings. At room temperature, current was increased up to 55 A, which is when the bobbin started to burn. However, at cryogenic temperature, current was increased up to 240 A, which is when the copper wire melted and opened the circuit. Due to the difference in the maximum current conducting capability of the copper winding in a bath of liquid nitrogen and at room temperature, the achievable energy density of coreless inductors at cryogenic condition can be much higher than the ambient temperature inductor even though it cannot use magnetic cores. In other words, the same energy density can be achieved by using thinner wires with lower ampacity but with more number of turns to increase inductance. Since energy stored in an inductor is proportional to the square of the current and the inductance is proportional to the square of the number of turns, reducing the diameter of the conductor and winding more number of turns will provide similar results in terms of energy density as long as the cooling power is maintained. The results show a significant advantage in terms of volumetric power density and gravimetric power density for future cryogenic power applications.

4. Outlook
In the near future, we plan to investigate the capacitor and inductor performance in greater detail. Especially, when it comes to the inductor design, we plan to add more layers of windings. The associated cooling, current density, inductance, and energy density of the inductor with multiple windings will be investigated. To exploit the superior cooling power of liquid nitrogen, spacers will be introduced in the inductor design and the impact of orientation on the inductor cooling and energy density will be studied. Furthermore, various means of keeping the magnetic core in cryogenic conditions will be considered since having a magnetic core is a huge advantage for maximizing inductance.

5. Conclusions
The feasibility of developing cryogenic capacitors and inductors was studied. We reported a variety of metallized film capacitors tested at ambient and at cryogenic conditions, and the results showed an increase in capacitance and voltage rating in a bath of liquid nitrogen. In addition, we compared the energy density of an ambient inductor that has a ferrite magnetic core and a cryogenic inductor that does not have a core. The results showed that the energy density of a coreless inductor operated in a bath of liquid nitrogen could be higher than an inductor operated at room temperature with a core. Although inductance was lower due to the lack of magnetic cores, much larger current could be used in liquid nitrogen due to the substantially enhanced cooling that liquid nitrogen provides and the enhanced electrical conductivity of the wires. As a result, the energy density of coreless cryogenic inductors can be comparable or higher than that of ambient inductors with magnetic cores. In summary, the findings of this study show great promise in utilizing conventional technologies in cryogenic applications as well as in developing cryogenic passive components for cryogenic power electronics.

6. References
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