IOP Conf. Series: Materials Science and Engineering **1302** (2024) 012026 doi:10.1088/1757-899X/1302/1/012026

GaN HEMT and Air Core Magnetics based Power Converters Evaluations at Cryogenic Temperature

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Abstract. Cryogenic power electronics is both advantageous and indispensable in many applications, like deep space probe, military electric vehicle, magnetic resonance imaging etc. Among different semiconductors, the gallium nitride (GaN) high electron mobility transistor (HEMT) is the most promising candidate for cryogenic applications with significant conduction loss and switching loss reductions. Moreover, there is no carrier freeze out effect for the GaN HEMTs, which is applicable in extreme low temperature operating conditions. In this work, the efficiency of GaN HEMTs based power converters with different power levels (from several Watts to several kiloWatts) are evaluated at cryogenic temperature. Three different commercial GaN HEMTs are used in these power converters, including the Texas Instruments LMG5200 80 V GaN half-bridge power stage with integrated gate driver, the GaN Systems 650 V bottom-cooled GaN HEMT GS66516B, and the 650 V top-cooled GaN HEMT GS66516T from GaN Systems. Moreover, two different cryogenic power converter evaluation methods (cryogenic chamber and liquid nitrogen channeled through cold plate) are investigated. Three of these power converters are evaluated by using a cryogenic chamber and such that the converter operating environment temperature can be regulated. One of the power converters is evaluated by using liquid nitrogen (LN2) channeled through a cold plate, where the gate driver can be designed to operate at non-cryogenic temperatures to ensure the safe operation of the system. Due to the degraded performance of conventional magnetic components, air core magnetics are used in these power converters to improve the converter efficiency. Efficiency improvements at cryogenic temperature are observed for all the GaN HEMTs and air core magnetics based power converters, which are promising for cryogenic power electronics applications.

1. Introduction

Cryogenic power electronics has been regarded as the next step to improve the power electronics converters efficiency and power density [1]. Cryogenics technologies are promising to be used in electrified transportations, such as maglev and aircraft. Fig. 1 shows the aircraft structure of the Advanced Superconducting & Cryogenic Experiment powertrain Demonstrator (ASCEND) program launched by airbus [2]. The superconducting machine and cables technologies are used to achieve near zero losses. Power electronics converters are used to drive the superconducting machine, which are also designed to operate at cryogenic temperatures to achieve high power conversion efficiency.

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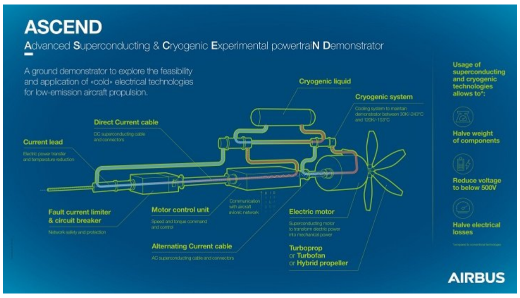


Figure 1. Aircraft structure of the Advanced Superconducting & Cryogenic Experiment powertrain Demonstrator (ASCEND) program launched by airbus [2].

To investigate the cryogenic power electronics, researchers from different groups have been working on the following aspects: 1) cryogenic characterizations of power electronics components, which can help understand their performances at cryogenic temperatures and provide guidelines for cryogenic power converters design; 2) cryogenic power converters design and implementation, which further validates the feasibility and advantages of cryogenic power electronics. Extensive research has been made on the cryogenic characterizations of power electronics components, including power semiconductors and passive components [3]-[15]. From the characterization results, it can be concluded that gallium nitride (GaN) high electron mobility transistor (HEMT) is a very promising candidate for cryogenic applications due to its significant reductions of on-state resistance and switching loss. Most of the core materials have degraded performances at cryogenic temperatures. However, there is few literature focus on the cryogenic power converters characterizations. In [16], the commercial low power off-the-shelf power converters are evaluated at cryogenic temperatures. In [17], a 1 kW GaN HEMT based flying capacitor multilevel inverter is designed and characterized at near cryogenic temperature. The efficiency performances at low temperatures are improved and loss breakdown analysis are provided to facilitate the understanding of power converters' performances at low temperatures. A cryogenically-cooled inverter is designed and tested in [18] for aircraft applications, where the Si MOSFET is selected as the power device.

In this work, the GaN HEMT and air core magnetics based power converters with different power levels (from several Watts to several kiloWatts) are evaluated at cryogenic or near cryogenic temperatures. These power converters can be served for various applications. Three different commercial GaN HEMTs are used in these power converters, including the Texas Instruments LMG5200 80 V GaN half-bridge power stage with integrated gate driver, the GaN Systems 650 V bottom-cooled GaN HEMT GS66516B, and the 650 V top-cooled GaN HEMT GS66516T from GaN Systems. Moreover, different cryogenic or near cryogenic converter evaluation methods are investigated. Three of these power converters are evaluated by using a cryogenic chamber and such that the converter operating environment temperature can be regulated. However, the maximum power is limited by using this test method due to the malfunction of the cryogenic chamber when the system power loss is large. One of the power converters is evaluated by using liquid nitrogen (LN2) channeled through a cold plate, where the gate driver can be designed to operate at non-cryogenic temperatures. Due to the degraded performance of conventional magnetic components, air core magnetics are used in these power converters to improve the converter efficiency.

The rest of this paper is organized as follows. Section 2 reviews the key power electronics components at cryogenic applications and point out the promising candidate for cryogenic applications. The individual power converters' performances are evaluated in Section 3. Finally, conclusions are drawn.

2. Review of Key Power Electronics Components Performances at Cryogenic Temperatures

In this Section, some key power electronics components' performances at cryogenic temperatures are reviewed and compared. All these characterization results are from our research group, they also agree well with the literature.

2.1. Semiconductors

There are various types of power semiconductors, including Silicon (Si) Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Si Insulated Gate Bipolar Transistor (IGBT), Silicon Carbide (SiC) MOSFET, and Cascode Gallium Nitride (GaN) Field Effect Transistor (FET), and GaN High Electron Mobility Transistor (HEMT). Fig. 2 shows the normalized on-state resistance (the ratio between the room temperature on-state resistance value and the value at cryogenic temperature 93 K) comparison of these power devices. It can be seen that both Si devices and GaN devices demonstrate significant on-state resistance reductions at cryogenic temperature, which will lead to conduction loss reductions for power converter applications. For sub-LN2 temperatures, the Si and SiC devices have the carrier freeze out effect and the devices stop working at certain temperatures. However, the GaN HEMT devices do not have carrier freeze out effect, which can be applied for sub-LN2 temperature applications. Fig. 3(a) shows the normalized turn-on switching loss comparisons for different power devices. The turn-on switching loss for GaN HEMT is reduced around 20% at near cryogenic temperature. The turn-on switching loss for the Si devices remains almost unchanged. On the other hand, the SiC MOSFET has degraded turn-on switching performance at near cryogenic temperature.

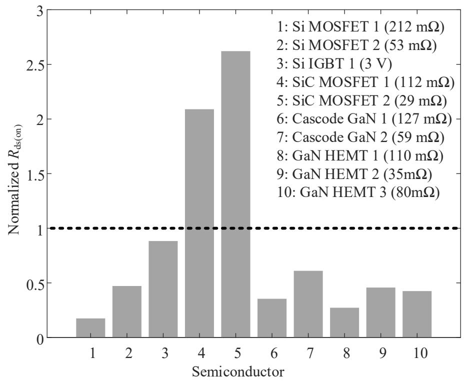


Figure 2. Normalized on-state resistance comparisons for different power devices at 93 K.

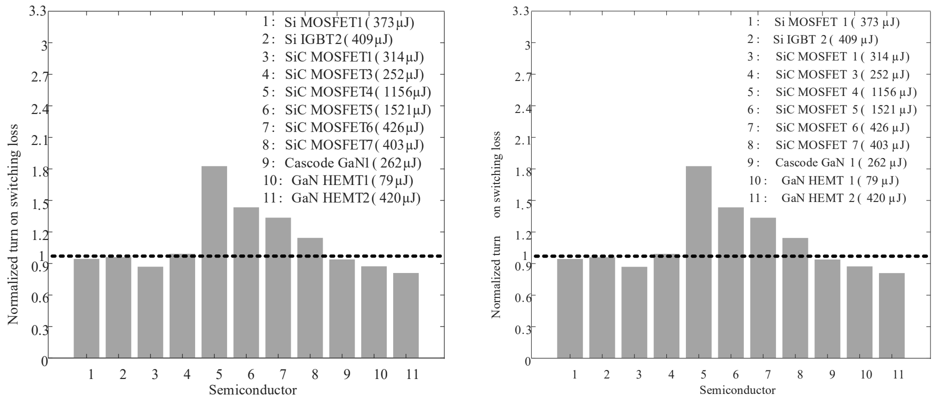


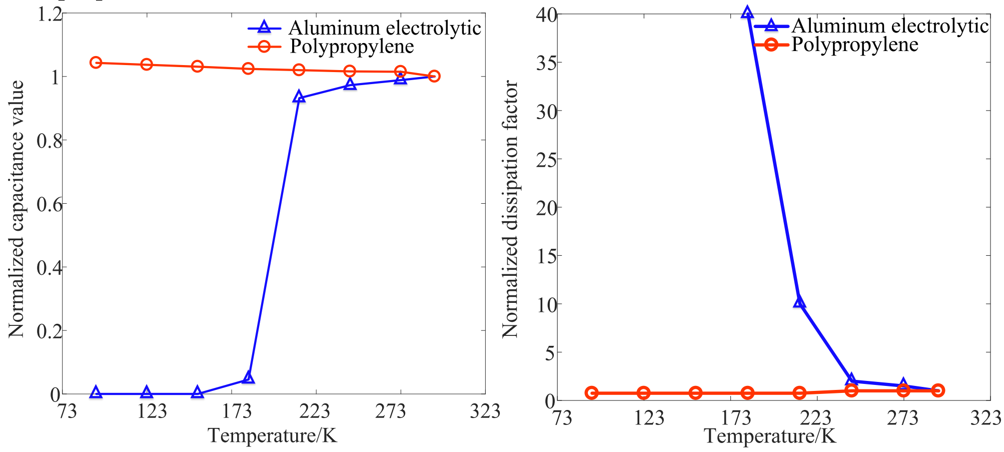
Figure 3. Normalized turn-on and turn-off switching loss comparisons for different power devices at 93 K.

Fig. 3(b) shows the normalized turn-off switching loss comparisons for different power devices. The turn-off switching loss of Si devices are reduced significantly at near cryogenic temperature, while the turn-off switching loss for GaN HEMT remains almost unchanged. For wide band gap (WBG) devices, the turn-on switching loss is much greater than the turn-off switching loss. Therefore, for hard switching operations, GaN HEMT based power converters have more switching loss reductions.

Moreover, the breakdown voltage for GaN HEMT remains unchanged at cryogenic temperatures [3]. Overall, GaN HEMT is a very promising candidate for cryogenic applications. In this article, the GaN HEMT devices are selected to build the cryogenic power converters.

2.2. Passive Components

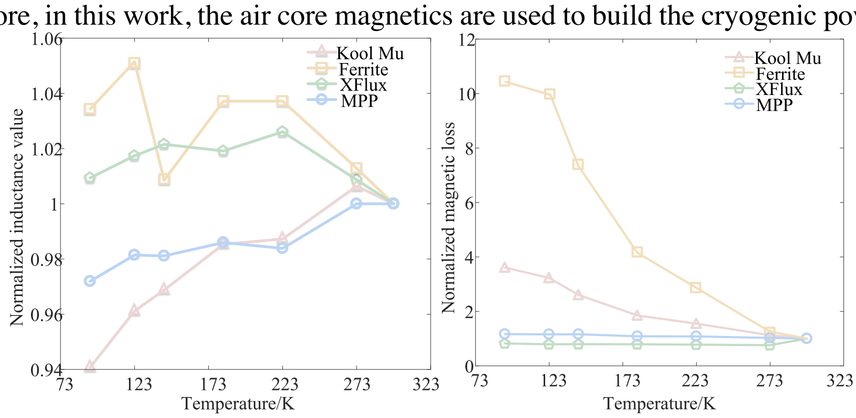
Fig. 4 shows the capacitance and dissipation factor comparisons for film capacitor (polypropylene) and aluminum electrolytic capacitor at low temperatures. The evaluated film capacitor has stable capacitance and dissipation factor over the entire low temperature range, which is desired for cryogenic applications. On the other hand, the aluminum electrolytic capacitor stops working around 223 K and this is possibly due to the electrolyte being frozen and therefore losing its conductivity at low temperatures [22].



(a) Normalized capacitance (b) Normalized dissipation factor

Figure 4. Normalized capacitance and dissipation factor comparisons for two different capacitors at room temperature and at 93 K [19].

Fig. 5 shows the inductance value and core loss for various types of magnetic cores under different temperatures. The conventional ferrite core loss increases significantly at cryogenic temperatures, which is not suitable for this application. Other types of magnetic cores are also not cryogenic friendly in terms of loss. Therefore, in this work, the air core magnetics are used to build the cryogenic power converters.



(a) Normalized inductance (b) Normalized core loss

Figure 5. Normalized inductance and core loss comparisons for different magnetic cores at room temperature and at 93 K [19].

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3. Cryogenic Power Converters Efficiency Performance Evaluations
Please note that for the evaluated power converters, the cooling loss is not considered by considering that free cooling is available in liquid hydrogen-powered airplanes [23].

3.1. Converter 1: 2.5 MHz 4 W LMG5200 based inductive power transfer (IPT) converter

Fig. 6 shows the prototype of converter 1. The Texas Instruments LMG5200 80 V GaN half-bridge power stage with integrated gate driver is used as the primary inverter, which is capable of 10 MHz switching frequency operation. The wireless power transfer technology (primary series compensated and secondary series compensated topology) is used, which can provide sufficient voltage isolation between the primary side and secondary side. The voltage doubler rectifier is adopted and the Si based Schottky diodes are used for the rectifier. The selected operating switching frequency is 2.5 MHz and the rated output power is 4 W. The converter input voltage is 20 V and the output voltage is also around 20 V. A possible application of this power converter is the gate driver power supply. The isolation can be easily satisfied by designing the airgap, which is favored for medium voltage applications.

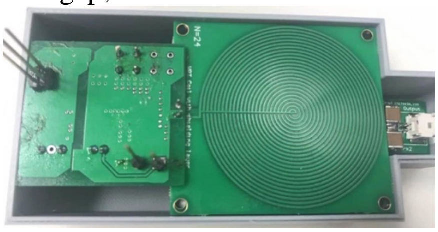

Figure 6. Prototype of converter 1.

Fig. 7 shows the efficiency performance of converter 1 at different operating temperatures. It is clear that the converter efficiency increases with the decrease of operating temperature. The converter efficiency at room temperature is 58.56%, and its efficiency increases up to 78.2% at 93 K. The major contributions for the efficiency improvement at cryogenic temperature can be summarized as follows: 1) Conduction loss reduction of GaN HEMT: due to the reduction of GaN HEMT on-state resistance, the power device conduction loss is reduced. However, since the soft switching is achieved for this topology, the switching loss reduction is not significant or remains almost unchanged; 2) Conduction loss reduction of wireless coils and parasitic resistances: the printed circuit board (PCB) copper trace resistance reduces at low temperatures. On the other hand, the forward voltage drop for the Si diode increases at low temperatures [3]. However, the overall system efficiency is dominated by the conduction loss of GaN HEMT and wireless coils.

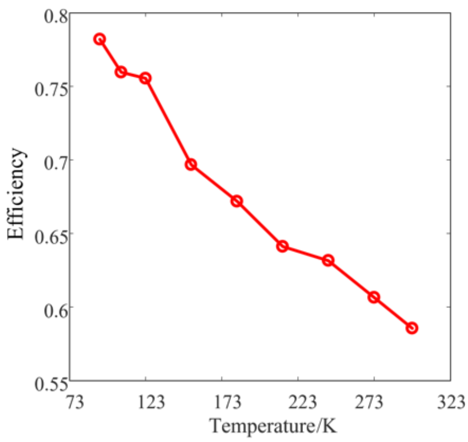

Figure 7. Efficiency performance of converter 1 at different temperatures.

3.2. Converter 2: 500 kHz 80 W LMG5200 based Buck converter

Fig. 8 shows the prototype of converter 2. For converter 2, the same power stage as converter 1 is used. The system operating switching frequency is 500 kHz and the input voltage is 50 V, output voltage is 25 V. The air core inductor is used as the load inductor.

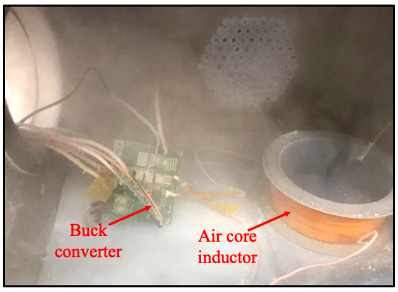

Figure 8. Prototype of converter 2.

Fig. 9 shows the efficiency performance of converter 2 under different operating temperatures. With 80 W output power, the converter efficiency improves from 90.67% at room temperature to 97.53% at 93 K. Different from converter 1, in addition to the conduction loss reductions of GaN HEMT and air core inductor, the turn-on switching loss reduction of the GaN HEMT also contributes to the efficiency improvement. Meanwhile, there is no Si diode for the Buck converter.

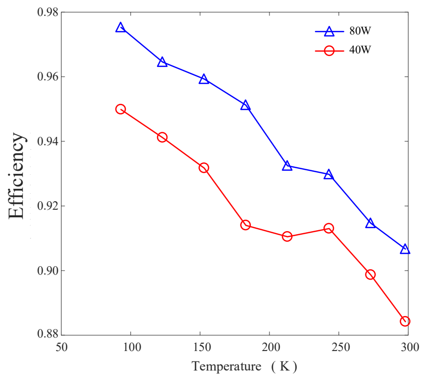

Figure 9. Efficiency performance of converter 2 at different temperatures.

3.3. Converter 3: 300 kHz 700 W GS66516B based Boost converter

The cryogenic characterization results for GaN HEMT GS66516B are presented in [4]. Both the on-state resistance and turn-on switching loss are greatly reduced at low temperatures. The Boost converter duty ratio is set as 0.5 and it is operating in open-loop condition. Fig. 10 shows the converter efficiency performance with different output powers under different operating temperatures. The minimum temperature operation for the converter is 143 K due to the malfunction of the gate driver. Compared to room temperature, efficiency improvements are observed over the whole output power range. The converter efficiency is improved from 89.90% at room temperature to 91.87% at 143 K when the output power equals to 50 W. When the output power increases to 700 W, the converter efficiency is improved from 95.96% at room temperature to 96.55% at 143 K. Moreover, the converter output voltage is increased at low temperature operations. Table 1 summarizes the output voltage comparisons between room temperature and 143 K. The efficiency improvement is mainly contributed by the conduction loss reductions of the GaN HEMT and air core inductor and the turn-on switching loss reduction of GaN HEMT. The output voltage is increased at low temperature since the parasitic resistance of the PCB board and components are reduced at low temperatures.

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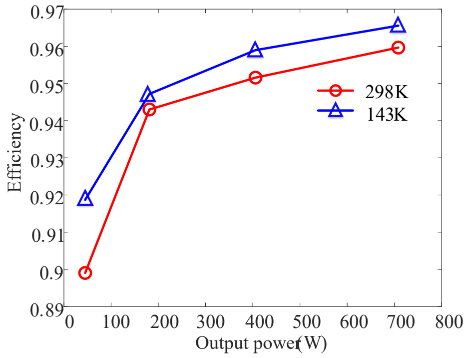

Figure 10. Efficiency performance of converter 3 at different temperatures.

Table 1. Output voltage comparisons at various input voltages and operating temperatures

Temperature	Input voltage: 50 V	Input voltage: 100 V	Input voltage: 150 V	Input voltage: 200 V
298 K	94.3 V	189.1 V	283.1 V	374 V
143 K	95.2 V	190.8 V	285.4 V	378.8 V

3.4. Converter 4: 150 kHz 2.2 kW GS66516T based four-switch Buck-boost converter

Most of the gate drivers are not working properly at cryogenic temperatures and they stop working at certain temperatures. To minimize the power device loss and ensure the safe operation of the system, the following cryogenic power electronics structure as shown in Fig. 11 is adopted [20, 21]. The gate driver is designed to operate at non-cryogenic temperatures and the optical fiber is used to transmit the control signal with high noise immunity. The top-cooled power device GS66516T is used to build the power stage. Fig. 12 shows the circuit topology of the four-switch Buck-boost converter, which is a symmetric topology and can be used for bi-directional power flow applications.

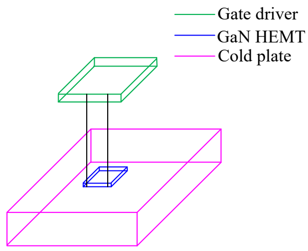

Figure 11. Cryogenic power electronics structure [20].

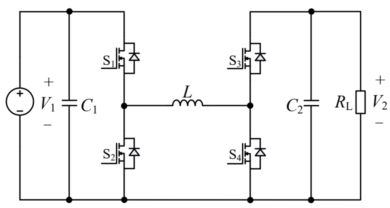

Figure 12. Four-switch Buck-boost converter.

Fig. 13 shows the experimental setup, where the air core inductor is used. Fig. 14 shows the efficiency curve comparisons at room temperature and cryogenic temperature when the output power equals to 600 W. Efficiency improvement is observed at cryogenic temperature. The converter is operating in Boost mode when the input voltage is lower than 120 V in Fig. 14 or 240 V in Fig. 15, and it is operating in Buck-boost mode when the input voltage is greater than 240 V. It is clear that the converter efficiency is improved at low temperature when compared with room temperature. Fig. 15 shows the converter efficiency performance at cryogenic temperature when output power equals to 2.2 kW.

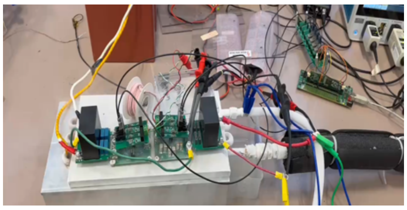

Figure 13. Experimental setup for the four-switch Buck-boost converter.

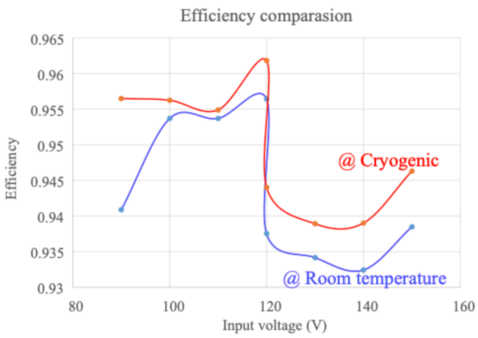

Figure 14. Efficiency comparison at room temperature and cryogenic temperature when output power equals to 600 W.

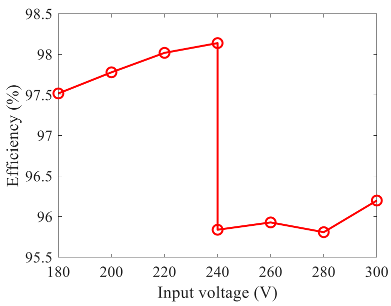

Figure 15. Efficiency performance at cryogenic temperature when output power equals to 2.2 kW.

3.5. *Summary of efficiency performance*

All the evaluated GaN HEMT and air core magnetics based power converters have demonstrated improved efficiency performance at cryogenic or near cryogenic temperatures. The individual converter efficiency performances are summarized as follows: 1) 2.5 MHz 4 W LMG5200 based inductive power transfer (IPT) converter: the converter efficiency at room temperature is 58.56%, while this value is increased up to 78.2% at 93 K; 2) 500 kHz 80 W LMG5200 based Buck converter: the converter efficiency increases from 90.67% at room temperature to 97.53% at 93 K; Further, the integrated gate driver for the LMG5200 works properly at LN2 temperature; 3) 300 kHz 700 W GS66516B based Boost converter: the converter efficiency at rated output power and room temperature is 95.97%, while the converter efficiency increases up to 96.56% at 148 K. The converter is not evaluated at even lower temperatures due to the malfunction of the gate driver; 4) 150 kHz 2.2 kW GS66516T based four-switch

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Buck-boost converter: a cryogenic power electronics structure is adopted to avoid the malfunction of gate driver and the cold plate is used to achieve cryogenic temperature.

Based on the individual components loss analysis, there are two major reasons for efficiency improvement at cryogenic or near cryogenic temperatures for these power converters: 1) switching loss and conduction loss reductions for GaN HEMTs; 2) conduction loss reductions for air core magnetics since the copper resistance is reduced at cryogenic temperature. Overall, GaN HEMT and air core magnetics-based power converters are very promising for cryogenic applications. Please note that for the evaluated scenario, liquid hydrogen is used as fuel cell and the penalty of cooling power electronics systems is not important. In addition, it is not necessary to keep power converters at cryogenic temperature during the whole operation range since the efficiency improvement can also be achieved at non-cryogenic temperature.

4. Summary

In this article, four GaN HEMT and air core magnetic based cryogenic power converters are evaluated. Some important conclusions can be drawn from these experimental results: 1) GaN HEMT is a promising candidate for cryogenic applications with conduction loss and switching loss reductions. Meanwhile, there is no carrier freeze out effect for GaN HEMT, which can be applied to extreme low temperature applications; 2) conventional magnetic cores have degraded performances at cryogenic temperature. The air core based magnetics have improved performance since the resistivity of the conductor is reduced at cryogenic temperature. Moreover, the superconducting material can be used to construct the air core magnetic and further improve the components performance by reducing the ohmic losses; 3) the GaN HEMT based half-bridge module with integrated gate driver from Texas Instrument works properly at liquid nitrogen temperature. However, other gate drivers are not working properly at cryogenic temperature. Therefore, a cryogenic power electronics structure is used to maximize the benefit of GaN HEMT and ensure safe operation of the gate driver; 4) all evaluated power converters have shown efficiency improvement at cryogenic or near cryogenic temperatures. The major contributions of these efficiency improvement come from the conduction loss reductions of air core magnetics and GaN HEMT power devices. Overll, GaN HEMT and air core magnetic based power converters are promising for cryogenic applications with improved system efficiency performance.

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Acknowledgments

The information, data, or work presented herein was funded in part by the NASA ULI: Development of the Cryogenic Hydrogen-Energy Electric Transport Aircraft (CHEETA) Design Concept under Award Number 80NSSC19M0125.