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Review of cryogenic power conversion and its potential in future all electric transportation systems: from silicon age to WBG era

F Luo[1], and M Ul Hassan[1]

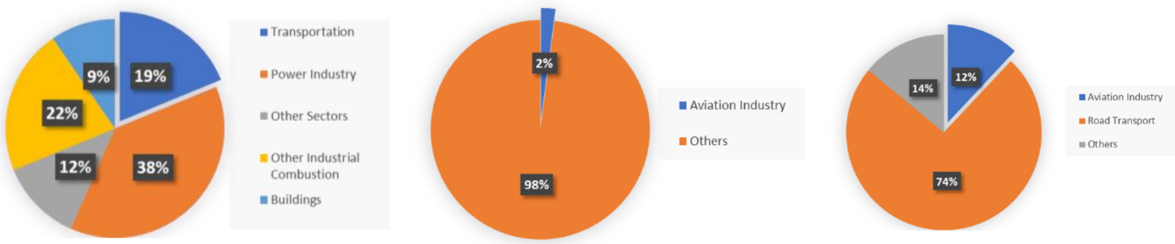
[1]Stony Brook University, Stony Brook, NY, 11794, United States

E-mail: fang.luo@stonybrook.edu

Abstract. Cryogenic power electronic conversion (< 123 K) is expected to offer higher efficiencies for future all-electric transportation platforms. Low temperature operation of converters together with integration of wide bandgap devices (WBG) can enable higher switching frequencies with reduced filtering components. This paper briefly reviews the passive components involved in the development of a cryogenic converter. The paper also reviews in detail the converter development with WBG devices by far, and provides a discussion on benefits achieved, and challenges in terms of auxiliary components and measurements. The last part of the paper gives a discussion on envisioned challenges, and different research directions for future superconducting power conversion systems.

1. Introduction and Background

Power electronic converters contribute an integral part in any power conversion system ranging from renewable energy systems, electric vehicles, and future electric aircraft as well. Considering annual emissions of fossil CO_2, transportation industry has been ranked third major contributor globally with a share of 19 % [1]. Similarly, the aviation industry has been counted to contribute 2 % of all human induced CO_2 emissions , whereas aviation industry contributes almost 12 % to the overall CO_2 emissions [2]. These trends have been shown in Fig. 1 respectively.



(a) (b) (c)

Figure 1. (a) Total global annual emissions of fossil CO_2 [1] **(b)** all human induced CO_2 emissions [2], and **(c)** CO_2 emissions from transport sources [2]

Based upon these statistics, numerous international aviation organizations have defined emission goals for future electric aircraft. In 2009, the international civil aviation organization (ICAO) set goals of carbon neutral growth from 2020 onwards [3]. The goals primarily consisted of short term and long-term actions. Short term actions include a) increase in fuel efficiency by 1.5 % per annum between 2009 and 2020, b) shifting to sustainable aviation fuels, and numerous operations and infrastructure measures. As part of long-term actions, a 50 % reduction in net CO_2 emissions by 2050 is targeted as of 2005 levels, which can mostly be achieved by changing the aircraft and engine technology. A pictorial depiction of these action plans is shown in Fig. 2. Similar to ICAO, the international air transport association (IATA) also adopted a ‘fly net zero’ program with similar objectives [4].

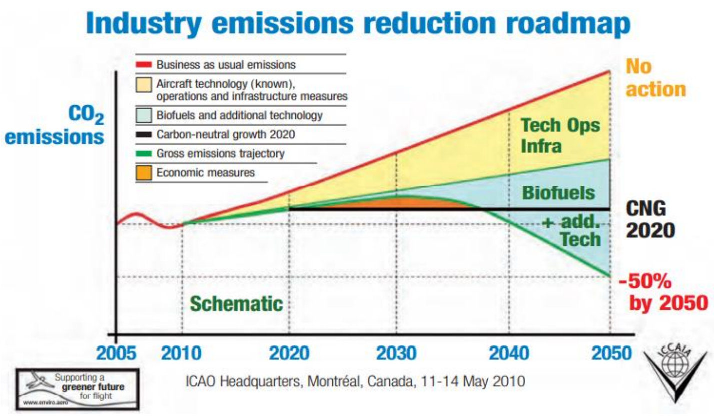
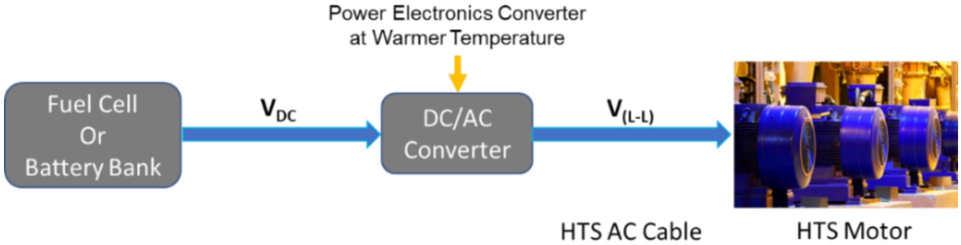
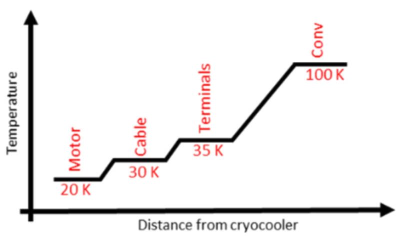


Figure 2. CO_2 emission reduction measures over time [3]

As part of a long-term solution which involves innovation in aircraft technologies, numerous efforts and initiatives were launched towards electrification of aircraft. Airbus has planned to announce the best combination of hydrogen technologies by 2025 in pursuit of zero emission aircraft, whereas battery energy storage based, and liquid hydrogen storage with fuel cell conversion has also been considered in other studies [5-7]. NASA has also sponsored a project namely center for high-efficiency electrical technologies for aircraft (CHEETA). The project funded exploring the usage of liquid hydrogen (LH_2) energy storage for full electric aircraft (FEA) where on-board cryogenic system to store and maintain LH_2 system was considered [8]. The goal of the sponsored program was to develop highly efficient cryogenic power electronic conversion (CPEC) system targeting following benefits: a) CPEC has the potential to increase overall semiconductor efficiency and power density, b) superconducting machines combined with CPEC will have a significant effect towards high density power conversion systems, and c) cryogenics and superconducting technologies will be present on-board future battle ships and aircraft, primarily in motors and generators. Reviews about different components and systems in existing CPEC have been provided in [9-11], however this paper discusses the benefits and challenges associated with WBG era. For such a CPEC, a power electronic converter has been placed at cryogenic temperature (<123 K) in contrast to conventional approach of its operating at room temperature. Both the conventional and proposed approach have been shown pictorially in Fig. 3 respectively.



(a)



(b)

Figure 3. (a) Traditional power electronic converter approach where converter operates at room temperature and drives a high temperature superconducting motor **(b)** CHEETA adopted approach, where converter is placed downstream cryogenically cooled overall system

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2. Structure of a Cryogenic Converter

Similar to any room temperature converter, a cryogenic converter majorly consists of three parts: a) passive components, b) gate driving auxiliary components, c) semiconductor device material. This section of the paper briefly covers and reviews the utilization of these components towards developing cryogenic power electronic converters.

2.1. *Passive components utilization in cryogenic power conversion*

Several articles have reported on the performance of capacitors in terms of dielectric loss, leakage losses and resistive losses at low temperatures. A brief summary about the performance of different capacitor types most suitable for cryogenic temperatures is presented below. The table summarizes the performance variation with respect to room temperature.

Table 1. Performance variation of most suitable capacitors with decreasing temperature [9-10]

PROPERTY	Y5V	NPO	POLYPHENYLENE SULFIDE (PPS)	POLYPROPYLENE	MICA
CAPACITANCE	Reduces	Stable	Stable	Stable	Stable
DISSIPATION FACTOR	--	Increases	Increases	Reduces	Reduces

Similar to capacitors, numerous research articles have reported the characterization of inductors at cryogenic temperatures. Table 2 summarizes the most suitable inductors in terms of their performance at cryogenic temperatures where powdered cores are listed to be operating better at lower temperatures. Besides core-based inductors, coreless inductors have also been employed together with superconductors for high power converters.

Table 2. Performance variation of most suitable inductors with decreasing temperature [9-10]

PROPERTY	MPC	KMC	HFC	NANO CRYSTALLINE
SATURATION FLUX DENSITY	--	--	--	Increases
HYSTERESIS/POWER LOSS	Increases	Stable	Stable	Increases
INDUCTANCE	Stable	Reduces	Stable	Reduces
QUALITY FACTOR	Increases	Reduces	Increases	--

2.2. *Gate driving auxiliary components for CPEC*

Numerous gate driving integrated circuits (IC) have been utilized in industry and academics, but very few have been reported to perform well at cryogenic temperatures. Most of the converters have been developed by placing them at room temperature, or away from the cold head of chamber (unknown

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temperature). Therefore, in this subsection of review, only the gate driving ICs currently in production and placed inside cold environment are reviewed. The ICs turned obsolete and not placed inside the cryo temperature have not been considered for the review. [12] implemented a boost type DC-DC converter using TC4427ACPA as a low side gate drive IC whereas [13], [14] designed and placed the gate drive inside the cryogenic chamber, successfully operating SiC devices down to 93 K. [15], [16] used similar gate drive IC inside the chamber but reported test results at 133 K and 143 K. [17] successfully implemented a gate drive at 77 K and presented a gate drive configuration for low temperature applications. [18] characterized a few gate drive ICs for cryogenic applications, but could not present them operating below 133 K.
In addition to gate driving ICs, numerous commercially off the shelf (COTS) auxiliary power supplies have also been characterized in [17-19], where not even a single reliable power supply was found from the characterization conducted. Therefore, a dedicated cryogenic auxiliary power supply was designed in [19].

2.3. *Semiconductor device suitable for CPEC*
Based upon potential applications of CPEC, significant research has been conducted in characterization of semiconductor devices including Si-MOSFETs, IGBTs and wide bandgap devices (WBG). Detailed summary about performance of different switching devices has been reported in [9-11]. As a quick conclusion, GaN devices show a monotonic improvement in both the conduction and switching losses with decrease in temperature and are the most ideal candidates for low voltage applications. However, for higher voltages, Si devices might be better until 93 K but they suffer from reduction in breakdown voltages. On the contrary, SiC devices show increase in conduction and switching losses and might not be the most suitable for CPEC because of decrease in efficiency at lower temperatures.

Table 3. Performance variation of semiconductor devices with decreasing temperature [10]

Device Type	On State Resistance	Threshold Voltage	Breakdown Voltage
Si-MOSFET	Reduces	Increases	Reduces
Si-IGBT	Reduces	Increases	Reduces
SiC-MOSFET	Increases	Increases	Stable
GaN HEMT	Reduces	Stable	Stable

3. Review of Cryogenic Converters Developed
This section of the paper reviews the progress towards development of CPEC. The review discusses the converter development in terms of Si and wide bandgap devices.

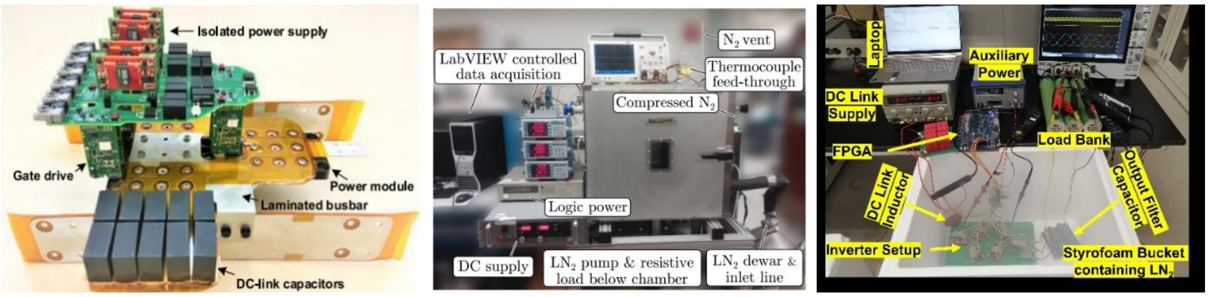
3.1 *Review of CPEC with Si devices*
From the perspective of cryogenic power electronic converters, only a few have been developed and reported; most of which are DC-DC converters using Si-based devices. In [20], a boost type DC-DC converter was implemented at 77 K using Si devices. [21] implemented a 150 W boost type DC-DC converter using Si devices, and in [22], a Si-based buck type three level DC-AC converter was implemented using Si devices.

3.2 *Review of CPEC with WBG devices*
This subsection of the paper reviews cryogenic power electronic converter development using wide bandgap devices. In [23], a MW class cryogenically cooled inverter has been designed using two 500 kW three level active neutral point clamped (3L-ANPC) inverters using SiC devices. However, the converter is operated only at room temperature. [24] presented a 1 kW, 3-level GaN based inverter for extreme cold applications. The converter was successfully tested until 133 K only, with input voltage of

150 VDC, and 45 V output. Authors reported a 16 % reduction in losses down to 213 K in comparison to RT. Similarly, a GaN based two level current source inverter was developed in [17]. Both the converter and gate driver were placed inside LN_2 Styrofoam bucket which maintains constant 77 K temperature. The converter was tested for 300 W inside LN_2 bucket and a 0.3 % increase in efficiency was reported. However, the authors claim a higher increase in efficiency when converter operated near rated operating conditions. In this paper, authors presented a detailed comparative study and trade-offs for the design of a cryogenic converter. The trade-offs are based on sizing of energy storage components, volume estimation of passive components and electromagnetic interference performance comparison. A summary about the converters developed with WBG devices has been presented in Table 4.

Table 4. Summary of recently developed cryogenic power electronic converters

Temperature	Device	Topology	Input Voltage	Output Voltage	Power	Switching Frequency	Efficiency
Cryogenically cooled inverters for future aircraft based on hybrid electric or turbo-electric propulsion	SiC MOSFETs	3L-ANPC 2 500 kW interleaved together	± 500 VDC	600 V RMS, 3 kHz fundamental	MW class inverter	70 kHz Switching, SVM	Not Reported
-140 °C LNG powered hybrid system	GaN HEMT 200 V,EPC 2034	Flying Capacitor Three Level	150 VDC	45 V RMS, 60 Hz, Resistive Load	1 kW, Single Phase	N/A, Phase Shifted Pulse Width Modulation	Peak efficiency of 96.7 at Full load conditions at -60degrees
LN_2 immersed inverter for future all electric aircraft	GaN HEMT 650 V	2L-CSI	270 VDC	300 VRMS	20 kVA	30 kHz	98+ % at 300 Watts



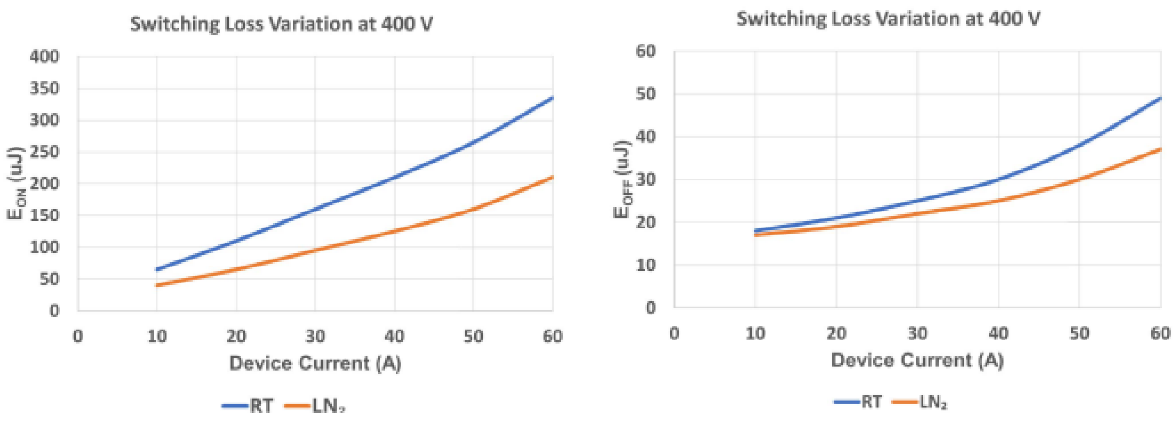
(a) (b) (c)

Figure 4. (a) MW class cryogenically cooled inverter with SiC devices [23] **(b)** GaN based 1 kW three level converter [24], **(c)** 20 kVA current source inverter [17]

3.3 *Benefits of CPEC*

To justify detailed trade-offs between establishing cryogenic temperature and converter, a detailed justification of benefits should be carried out, which is found missing. However, from converter operational losses and efficiency, [17] has reported an increase in power efficiency of 0.3 % when operating at 300 W. This increase in efficiency is expected to be higher when the converter gets loaded at higher power levels.

A similar attempt was made in [17] and an increase in switching speed and reduction in switching losses is reported. Fig. 5 shows operational differences between room temperature and LN_2 (77 K) on turn-on and turn-off voltages and the associated switching loss energies.



(a) (b)

Figure 5. (a) Turn-on switching loss variation **(b)** Turn-off switching loss variation for 650 V GaN device, adopted from [17]

4. Important Considerations for Low Temperature Converter Development

As part of overall converter development, numerous design and analysis challenges need to be investigated to ensure a reliable and complete converter development. From the research conducted and reported, a conclusion can be drawn that research on characterization of passive components and semiconductor devices is significantly mature. However, there needs to be more investigation and development about few items including:

4.1 *Gate driving components and auxiliary power supply*

Gate driving components and auxiliary power supply should be designed based upon the temperature induced switching speed variations and performances. This is important because most of the auxiliary power supplies in commercial domain are not designed for such applications and they stop operating at lower temperatures. [17] did a detailed analysis on COTS auxiliary power supplies and concluded just one of them operable at extreme low temperatures. A summary about their operation is presented in Fig. 6.

SUMMARY OF PERFORMANCE OF COTS APS WITH TEMPERATURE

Part Number	Manufacturer	Power (W)	Performance at LN_2	Efficiency at LN_2
PEM2-S5-D5-S	CUI INC	2	Consistent	Reduced to 30 %
PEME1-S12-S12-S	CUI INC	1	Consistent	Reduced to 34 %
MDS01M-12	Meanwell Web	1	Consistent	Reduced to 24 %
MDS01L-12	Meanwell Web	1	Consistent	Stopped working
TRV 1-1212M	Traco Power	1	Consistent	Stopped working
RV-0509S	Recom Power	2	Sometimes mal-operates	Negligible Reduction
R05P209S	Recom Power	2	Inconsistent	Negligible Reduction

Figure 6. Performance of numerous auxiliary power supplies, adopted from [17]

4.2 *Design of instrumentation and measurement methods*
Instrumentation and measurement methods need proper investigation and must be characterised especially for low temperatures. It has been observed by some researchers that improper measurement approaches might be counterproductive, and benefits of cryogenic operation might get underestimated [17]. Research on proper instrumentation becomes more important when the measurements are to be conducted from inside chambers involving feedthroughs and long interconnects.

4.3 *Design of analog and digital controllers*
To have a complex converter designed, there is need of analog ICs or digital controllers which act as brain of the converter and produce the required pulse width modulation (PWM). For such a purpose, design of analog and digital controllers must be given a thorough consideration as they are an essential part of converter development. As of now, none of the low temperature converters developed so far in public domain have reported their controllers placed inside the low temperature environment. This kind of approach might be affordable for Si-based converters, but for SiC and GaN devices, the approach will probably not be helping. The reason for this is their sensitivity to input gate loops bringing the pulse width modulation from the controller [17].

4.4 Affordable cryogenic chambers
Another area of concern towards more frequent research is development of cryogenic temperatures. Access to cheaper cryogenic chambers is also extremely critical for an easy and fast paced research towards CPEC.

5. Conclusion
In this paper, need for a greener aviation is emphasized by referring to reports from numerous international organizations. As a result, cryogenic power electronic conversion was adopted by different research and academic organizations with the goals of higher power efficiency and power density. The paper did a brief review of different converter components including passive components, semiconductor devices, and gate driving components. The paper also did a brief review of power electronic converters developed with Si and wide bandgap devices. Towards the end of paper, numerous challenges towards cryogenic converter development are highlighted which have been pointed it in different articles.

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