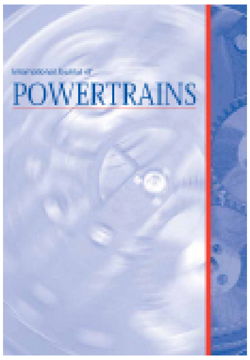

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Mustafeez Ul-Hassan, Yalda Azadeh, Asif Imran Emon, Fang Luo

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Review of power electronics converters and associated components/systems at cryogenic temperatures

Mustafeez Ul-Hassan*

Department of Electrical and Computer Engineering,
Stony Brook University,
New York, USA
Email: mustafeez.hassan@stonybrook.edu
and
Department of Electrical Engineering,
University of Engineering and Technology,
Lahore, Pakistan
Email: mustafeezulhassan@uet.edu.pk
*Corresponding author

Yalda Azadeh, Asif Imran Emon and Fang Luo

Department of Electrical and Computer Engineering,
Stony Brook University,
New York, USA
Email: yalda.azadeh@stonybrook.edu
Email: asifimran.emon@stonybrook.edu
Email: fang.luo@stonybrook.edu

Abstract: Increasing trends towards electrified transportation and future deep space missions target extremely low environmental operating temperatures of aircraft and spacecraft. For such applications, advantages associated with low temperature operation of power electronics converters, superconducting machines, energy storage devices, and current leads can significantly help improve the efficiency and density of integrated power conversion systems. Power electronics converters, being an integral part of such a conversion system, offer reduced losses, better switching speeds, and lesser size and weight. Similarly, superconducting machines are lighter and are more efficient at such temperatures. Owing to the improved performance of cryogenic power conversion systems compared to room temperature (RT) operation, a detailed review of low operating temperature power electronics converters and their constituent components including semiconductor devices, passive components, and superconducting machines is presented in this paper.

Keywords: cryogenic; low temperature; power electronics; devices; efficiency; power density; passive components; converters.

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Biographical notes: Mustafeez Ul-Hassan received his BSc and MSc in Electrical Engineering from the University of Engineering and Technology, Lahore, Pakistan, in 2013 and 2017 respectively. He is currently a third year PhD student at the State University of New York at Stony Brook, NY, USA. His research interests include using modern wide band gap (WBG) devices for high-power density converters for extreme low temperature applications. Prior to joining PhD program, he served as a Lecturer at one of the leading universities of electrical engineering in Pakistan. He is pursuing his PhD from USA funded by prestigious Fulbright scholarship.

Yalda Azadeh graduated from her Bachelor and Masters degrees from the University of Tabriz in 2014, and 2017, respectively. She is studying her PhD degree at the Stony Brook University. Her research interests include optimising the use of off-the shelf modules, studying interactions in component/system-level from different aspects like electromagnetic interference. She is also working on accelerated tests to extract system/components' degradation signatures and how they relate to lifetime.

Asif Imran Emon received his BSc in Electrical and Electronic Engineering from the Chittagong University of Engineering and Technology in 2015. He received his MS in 2020 from the University of Arkansas, Fayetteville, Arkansas, USA. He is currently a PhD student at the State University of New York, Stony Brook. His research interests include power module packaging of wide band-gap devices, efficient energy conversion and electromagnetic interference in motor drive.

Fang Luo received her Bachelor's and PhD in Electrical Engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2003 and 2010, respectively. He is currently an Empire Innovation Associate Professor, with the Stony Brook University, NY, USA. From 2007 to 2010, he was a joint PhD student at the Centre for Power Electronics Systems (CPES), Virginia Tech. From 2010 to 2014, he was with CPES, Virginia Tech. From 2014 to 2017, he was an Assistant Professor with The Ohio State University. In July 2017, he joined the University of Arkansas as an Assistant Professor and worked there till 2020. His research interests include turbo electric propulsion converters, high-power-density converter design, high density electromagnetic interference filter design, and power module packaging/integration for wide-bandgap devices.

1 Introduction

Development of low temperature power electronics has been given extensive attention recently because of their potential applications in modern transportation, medical diagnostics, wind power generation, and super conducting magnetic energy storage systems. The increased interest in cryogenic investigation relies upon the increased efficiency of power electronics converters, reduced size of superconducting machines, and thus improved overall system performance, enabling significant cost and weight reduction.

As indicated by NASA's ambitious targets for the next generation aircrafts (NASA, 2017), a move towards replacing pneumatic and mechanical systems with electrical systems has increased electrical power consumption in aircraft, thereby transitioning to a ‘more electric’ aircraft paradigm (Moir and Seabridge, 2011). For such aircraft, cryogenically cooled power converters and superconducting machines are proposed to improve the overall efficiency of the propulsion system (Latypov et al., 2011; Luongo et al., 2009). Similarly, 10–20 MW wind turbine generators can offer cheaper offshore wind energy by using superconducting technology as identified by DOE/NREL (Maples et al., 2010). These studies motivate using and developing power electronics which can be integrated with systems requiring cryogenic operating temperatures. Superconducting machines and air/spacecraft-based electronics are an example of such systems. Conventionally, power electronics to be used in the aforementioned applications required diligently designed cooling arrangements, thus adding size, weight, and development costs to the system (Elbuluk and Hammoud, 2005). Therefore, placing power electronics systems inside the cryogenic environment proves to be more feasible and economical (Gui et al., 2019a).

A cryogenic environment can be created with the help of liquid nitrogen, LN_2 (77 K), liquid hydrogen, LH_2 (33 K) or liquid helium, LHe_2 (4 K) depending upon the minimum operating temperature requirements. A power electronics converter for such applications possesses numerous components, connected to constitute a complete converter system. In this paper, the target is to review major constituent blocks of such a converter, i.e., power semiconductor devices and passive components. Although several articles have reported on the characterisation and performance of semiconductor devices, and passive components, a detailed review of types, performance, and limitations of power electronics converters for cryogenic temperatures (CT) is yet to be reported. In this paper, the cryogenic performance of different semiconductor devices is discussed in Section 2, whereas in Section 3 power electronics converter topologies, their ratings, and efficiencies are analysed. A brief discussion of the advantages and challenges about superconducting machines is provided in Section 4, whereas cryogenic cooling methods have been presented in Section 5, and the conclusion of the paper is provided in last section.

2 Power semiconductor devices for cryogenic applications

Characterisation of power electronics devices at CT plays an important role in determining the design and performance of cryogenic converters. Power devices can be characterised by placing both the device and its associated auxiliary components inside a cryogenic chamber. As has been reported in literature, most of the semiconductor devices have better electrical and thermal performance at lower temperatures, and hence better power conversion efficiencies. On-state resistance, threshold and breakdown voltage, forward voltage drop, and switching speed are a few of the parameters to be considered in the analysis of semiconductor devices.

2.1 Silicon MOSFET (Si-MOSFET)

Numerous articles have been published discussing the characterisation and advantages associated with operating MOSFETs near CTs. Advantages in terms of increased reliability; reduced inversion currents, increased electronic carrier mobility, and higher thermal and electrical conductivity are reported in Gaensslen et al. (1977), Kirschman

(1985) and Mauriello et al. (2000). At CT, they also have less leakage current, increased reliability and reduced thermal noise (Curcic and Wolf, 2005; Ye et al., 2006).

Si MOSFETs offer reduced on-state resistance down to low temperatures (Gaensslen et al., 1977; Giesselmann et al., 1996; Kirschman, 1985; Mauriello et al., 2000), thereby reduced conduction losses and higher over currents can be achieved (Giesselmann et al., 1996; Haldar et al., 2005). This reduction in on-state resistance is attributed to higher carrier mobility's and superior heat removal from devices at lower temperatures, thus resulting in the increased power handling of the devices. However, the on-state resistance of Si begins to increase when lowering the temperature below 70 K (Leong et al., 2010a).

Threshold voltage and transconductance increases are reported in Singh and Baliga (1992) as a MOSFET operates down to 77 K. Moreover, breakdown occurs at a reduced voltage level, which is due to increased mean free path of charge carriers from photon scattering (Giesselmann et al., 1996; Haldar et al., 2005; Leong et al., 2010b; Mueller, 1996).

The cryogenic behaviour of different types of MOSFETs down to 20 K is discussed in Leong et al. (2010b). The on-state resistance decreases until to 50 K, below which some CoolMOS devices showed carrier freeze out. Device characterisation from 420 K down to 80 K is provided in Schlogl et al. (1999). Ye et al. (2007) conducted a numerical simulation study of Si MOSFETs and compared their performance at room and low temperatures.

2.2 Silicon insulated gate bipolar transistor (Si-IGBT)

For RT applications, IGBTs are very common in medium power applications because of their reliability, availability, and lower cost. Like Si-MOSFET, their characterisation for cryogenic applications is also reported. For CT, the on-state forward voltage of IGBTs reduces linearly by around 30% because of increased carrier mobility (Sze et al., 2021; Yang, 2005), whereas reduction in switching losses can be up to 60% (Forsyth, 2006). IGBTs show increased gate threshold voltage due to a reduction of intrinsic carrier concentrations and trapped interface electrons (Singh and Baliga, 1995; Qi et al., 2018). In several articles, an increase in transconductance at low temperatures and a reduction in forward voltage drop down to 100 K is reported, below which it starts to increase due to carrier freeze out (Chow et al., 1991a, 1991b; Jia, 2008; Menhart et al., 1992; Singh and Baliga, 2012; Yang and Forsyth, 2003, 2004).

2.3 Silicon carbide MOSFET (SiC-MOSFET)

Wide bandgap (WBG) devices are becoming popular as they improve overall system reliability, volume, and power density. Among them, SiC offers higher efficiency, higher blocking voltages, and more current handling capabilities at much higher switching frequencies compared to conventional Si based devices. At RT, SiC devices have lower conduction losses, faster switching speeds and lower switching losses as compared to conventional Si devices. However, for SiC devices, on-state resistance and gate threshold voltage increase with a reduction in temperature (Gui et al., 2018). Two possible reasons for such a trend are the carrier freeze-out phenomenon and increased interface state density between SiC and SiO_2 (Chen et al., 2013; Gui et al., 2018). Like p-n junctions, the breakdown voltage of SiC MOSFETs drops at lower temperatures because of a longer mean free path of charge carriers (Hong et al., 2019). Characterisation of numerous SiC

MOSFETS at different voltage ratings is reported in literature showing increased on-state resistance and stable breakdown voltage (Chen et al., 2015; Chowdhury et al., 2017; Zhang et al., 2018).

2.4 GaN HEMT

Another type of WBG devices is the GaN high electron mobility transistor (HEMT) which also significantly improves device performance. Characteristics of GaN HEMTs are reported in Nela et al. (2020), Ren et al. (2018, 2019) and Zhang et al. (2018). On-state resistance of GaN HEMTs decreases with temperature (Nela et al., 2020; Ren et al., 2019; Zhang et al., 2018), which is attributed to non-carrier freeze out due to the presence of a two-dimensional electron gas (2-DEG) in its channel. Contrary to other switching devices, breakdown, and gate threshold voltage of GaN devices is almost constant with a reduction in temperature as reported (Ren et al., 2018).

At the end of this section, a brief comparison of the performance of different types of semiconductor devices at CTs compared to RT is summarised in Table 1.

Table 1 Summary of performance of power semiconductor devices

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 Power electronics converter topologies and associated passive components

It is important to understand the properties and performance of different types of passive components required either for the purpose of filtering or storing energy in a power electronics converter. Similarly, it is worthwhile to identify the integration of such components in different converter topologies, and understand their performance under varying operating conditions, like switching frequency, temperature and loading conditions. In this section of the paper, capacitors and inductors/transformers are characterised at CTs, and numerous existing cryogenic converter topologies are reported. In Subsection 3.1 details about the characterisation and performance of passive components involved are reported, whereas in Section 3.2 the types of converters developed, lowest temperature to which they were tested, type of semiconductor devices used, and filter components involved are presented.

3.1 Passive components

Power electronics converters are mainly comprised of semiconductor devices and passive components. Passive components include resistors, capacitors, and inductors, where the latter two may either be serving the purpose of energy storing or of filtering out ripples in currents or voltages or of filtering out other high frequency components. In this subsection, the characterisation and performance of such components at CT is discussed.

3.1.1 Capacitors

Several papers have reported on the performance of capacitors in low temperature applications. The dielectric properties, including dielectric losses, leakage losses, and resistive losses of materials for cryogenic applications is analysed down to LN_2 temperature (Mathes and Minnich, 1967). Ceramic and film power capacitors are characterised down to 88 K, where ceramic capacitors were found not only to be thermally stable, but capacitance also did not change (Hammoud and Overton, 1996). On the contrary, film capacitors degrade with temperature and their dissipation factor is reduced. Teyssandier and Prêle (2010) provided a comprehensive characterisation of capacitance and equivalent series resistance (ESR) for numerous capacitor types for LN_2 and LHe_2 temperatures. Changes in capacitance, dissipation factor, and ESR for numerous capacitors under LN_2 temperatures are discussed in Bank and Virginia (2009), Pan (2005) and Patterson et al. (1998). The behaviour of various types and values of film capacitors from different manufacturers are explored in sub LN_2 temperatures in Park et al. (2018). In Table 2, a summary of the performance of different capacitor types at CTs with respect to room temperature (RT) is presented.

Table 2 Summary of performance of capacitors at CT

Property	*X7R*	*Y5V*	*NPO*	*Polyester*	*Polyphenylene sulphide (PPS)*
Capacitance	Reduces	Reduces	Stable	Reduces	Stable
Equivalent series resistance	Increases	Increases	Stable	Increases	Reduces
Dissipation factor	Increases	--	Increases	Reduces	Increases
Property	*Polypropylene*	*Polycarbonate*		*Mica*	*Tantalum*
Capacitance	Stable	Reduces		Stable	Almost stable
Equivalent series resistance	Reduces	--		--	--
Dissipation factor	Reduces	Reduces		Reduces	Increases

3.1.2 Inductors

Like capacitors, the characterisation of inductors at CTs has been reported in literature as well. Gniewek and Ploge (1965) reports the AC core loss and DC magnetic properties at temperatures as low as 4 K for a variety of Fe-Si and Fe-Ni alloys. With lowered temperatures, thin grain-oriented Fe-Si material has a minor increase in loss, whereas using Fe-Ni alloys; hysteresis loss is increased in the order of 100%. Properties of ferrite materials at lower temperatures were reported down to 4.2 K (Dionne, 1997; Pannaparayil et al., 1991). Gerber (2002) investigated powdered magnetic cores, including moly permalloy powder cores (MPP), high flux core (HFC), kool Mμ cores (KMC), and ferrite cores down to temperatures of 93 K. For consistency, the same wire type and gauge of conductor was used to characterise the inductors from 1 kHz to 200 kHz. Inductance, quality factor, and resistance are measured as a function of temperature and frequency. MPP and HFC maintain a constant inductance, whereas

KMC and ferrite core's inductance decreases with temperature. Furthermore, resistance of all the inductors decreases because of the improved conductivity of copper at lower temperatures.

Chen et al. (2003) studied amorphous alloys and grain-oriented silicon steel materials for high temperature superconducting (HTS) transformers at a frequency of 50 Hz and 77 K temperature. The authors reported an increase in saturation flux density and core power loss with a decrease in temperature.

Quach and Chui (2004) measured the permeability of several core materials at liquid helium temperatures (4 K) to understand the core utilisation for inductive electromagnetic interference (EMI) filters in low temperature applications. Metglass 2714A has high permeability (greater than 10,000) at frequencies up to 100 kHz. On the contrary, cryoperm-10 has higher initial permeability, but this starts to roll off at about 100 Hz, thereby offering lower inductance for the high frequencies of an EMI filter. Similar characterisation of core losses for several ferrite compositions, as well as metallic ferromagnetic materials, are carried out down to 78 K in Claassen (2005) and Jankowski et al. (2014). Not only the relative permeability of ferrites decreases, but core losses for ferrites also increase by a factor greater than 10, whereas they increase by a factor of 3 and 40% for the nanocrystalline material and powdered core, respectively.

Table 3 Summary of performance of inductors at CT

Property	*Fe-Si*	*Fe-Ni*	*MPC*	*KMC*	*HFC*
Saturation flux density	--	--	--	--	--
Hysteresis/ power loss	Increases	Increases	Increases	Stable	Stable
Inductance	--	--	Stable	Reduces	Stable
Quality factor	--	--	Increases	Reduces	Increases
Property	*Ferrite*	*Grain oriented Si steel*	*Amorphous steel*	*Finemet*	*Nano crystalline*
Saturation flux density	Increases	Increases	Increases	--	Increases
Hysteresis/ power loss	Increases	Increases	Increases	Increases	Increases
Inductance	Reduces	--	--	--	Reduces
Quality factor	Reduces	--	--	--	--

A DC-DC converter is designed to estimate the total losses in powdered iron inductor at 173 K in Azofeifa and Barth (2018). Copper losses decrease due to the increased conductivity of the wire. However, core losses increase, thus keeping overall losses to be constant. Recently, characterisation of ferrite and nanocrystalline based core materials have been investigated down to 93 K (Chen et al., 2018). The permeability of both materials decreased by a factor of 7–8 and 2, and core losses increased by 10 and 2 times respectively, whereas the saturation flux density for both showed a slight increase. Park et al. (2020) conducted a study to understand the role of coreless inductors in cryogenic applications at RT and LN_2 temperature. It is shown that such inductors offer lower mass, and thus can offer better power density for power electronics converters. The energy density of coreless inductors at CTs can be much higher than that at ambient temperatures. In Table 3, a summary of the performance of different inductor types at CT with respect to RT is presented.

3.2 Existing developed power electronics converters

Although much research has been done to characterise semiconductors and passive components at CT, not many converters are reported for such applications. The converters developed are generally reported to have lower power ratings and control circuitry which is placed outside the cryo-environment. In this section of the paper different converter topologies developed for CTs, their power rating, the type of semiconductor devices used, and nature of filtering components are reviewed.

3.2.1 DC-DC converters

Ray et al. (1995) designed and tested a pulse width modulated (PWM) buck type 42 V to 28 V, 175 W converter at LN_2 temperatures. The converter operates at a 50 kHz switching frequency using Si devices, with an efficiency improvement of 1.2% when operating at low temperatures. MPP core and polypropylene film capacitors are utilised for filtering purposes. Both the power circuit and filter components are placed inside the chamber while the control circuit is at RT. Ray and Patterson (1995) reported a wide operating temperature range for PWM boost converters at 150 W operations with an input of 24 VDC and 48 VDC output. The converter operates with Si devices and has an efficiency of 92.2% at around 90 K, with the power circuitry and the MPP based input energy storage inductor being placed inside the cold environment, with the rest of the electronics at RT. A similar boost converter is designed by Ray et al. (1996) for operation at LN_2 temperatures but makes use of a HTS inductor. This can be compared with the performance of an MPP core-based inductor. It is concluded that the HTS inductor has no significant performance improvement compared to MPP inductor due to its higher AC losses. To see the impact of the HTS inductor, the authors proposed higher power and lower switching frequency converters. Perez-Guerrero et al. (1997, 1999) presented the performance of a three-level buck converter operating down to 77 K at a switching frequency of 50 kHz and converting 48 VDC to 12 VDC with a rated power of 60 W. Perez-Guerrero et al. (1999) implemented the closed loop control with integrated circuits placed inside the cold environment whereas the input power supply and measuring instruments are outside. Kool Mμ core and polypropylene film capacitors are utilised for filtering purposes.

Investigation of high-power density converters with advanced devices, and commercially available passive components is reported frequently for RT applications. However, Elbuluk et al. (2000) and Gerber et al. (2000) investigated the performance of such type of converters for low temperature applications for deep space missions. DC-DC converters from numerous manufacturers with power ratings around 10 W, and variable inputs ranging from 9–75 VDC have been tested down to 83 K. Variation of the output voltage and efficiency with respect to temperature is recorded. Elbuluk et al. (2002) carried out a similar investigation for a 10 W DC-DC converter module with an input voltage of 16–40 VDC and an output of 3.3 VDC. Output voltage regulation, efficiency, and ripple characteristics of the converter are analysed down to 133 K. Li et al. (2005) analysed the performance difference for a boost converter operating at RT and at LN_2 temperatures. The performance of a semiconductor switching device is investigated for both soft and hard switched configurations. The advantages associated with soft and hard switched converters at CT are more proficient as compared to its RT counterpart.

Jia and Forsyth (2006) investigated the performance of 500 W buck type topologies with hard switched, soft switched and synchronous rectifier configurations tested down to 20 K. Different power MOSFET devices and diodes are studied and a reduction in semiconductor losses up to 85% is reported. Both the power and gate drive circuits are placed inside the cold chamber for characterisation. As part of the observation, semiconductor losses in a soft switching converter are reduced to 15% at CT as compared to their RT reference. Bourne et al. (2008) characterised numerous passive and active components, and a SiGe asynchronous controller for the development of a 24 VDC, 20 W full bridge DC motor drive for an ultra-wide temperature range (43 K–393 K). The targeted permanent magnet (PM) based DC motor drive is developed and tested down to 89 K using Si devices (Garrett et al., 2007). Also, the results for characterisation of different resistors, capacitors, gate drivers, and active components are presented. Information about failed components like SiC based devices, gate drivers, and controllers is also provided. Chen et al. (2016) designed an efficient 40 kW boost converter using CoolMOS MOSFETs and a HTS inductor. 85% reduction from conduction losses and 87% reduction in overall system losses is reported down to 77 K operation as compared to RT. Usage of HTS GdBCO inductor enables reduction of conductor loss from 104 W to mere 9 W.

3.2.2 DC-AC converters

Low temperature and high-power inverters will be key components for future aircraft and transportation applications. Like DC-DC converters, DC-AC converters at low temperatures will offer increased efficiency, lower volume, and thereby increased power density.

Wang et al. (2019) proposed the design of a MW class cryogenically cooled inverter for electric aircraft applications. Two 500 kW three level active neutral point clamped (3L-ANPC) inverters are paralleled through interleaved inductors for an output voltage of 600 V. The converter is operated at a switching frequency of 70 kHz with space vector modulation (SVM) using SiC devices. Testing of the converter is carried out only for RT, and full load cryogenic testing is not yet reported.

A 1 kW, 3-level GaN based inverter for CT, and hybrid electric aircraft applications are presented in Barth et al. (2017, 2020). The converter was successfully tested down to 133 K with an input voltage of 150 VDC, and a 45 V output. The concept of ceramic based flying capacitors is utilised for the converter operating with 200 V GaN devices at a switching frequency of 120 kHz. A 16% reduction in losses is reported down to 213 K in comparison to the RT. Gui et al. (2019b) reported a 40 kW cryogenically cooled inverter, operating at switching frequency of 140 kHz. 3L-ANPC topology with Si MOSFETs is utilised in the designed converter for output of 600 V. Series cascading of Si devices is utilised, where the converter has full load efficiency of 97.8% with no reference to operating temperature.

Table 4 Summary of different converters for cryogenic applications

Ref.	*Lowest temperature*	*Type*	*Device*	*Topology*	*Input voltage*	*Output voltage*	*Power*	*Switching frequency*	*Efficiency*	*Comments*
Ray et al. (1995)	77 K	DC-DC	Si MOSFET	PWM Buck	42 VDC	28 VDC	175 W	50 kHz	Efficiency improvement from 95.8% to 97%	Power circuit, filter inductors and capacitors inside Dewar.
Ray and Patterson (1995)	~90 K	DC-DC	Si MOSFET	PWM Boost	24 VDC	48 VDC	150 W	50 kHz	92.2% efficient at cold temperature	Power circuit and inductors inside the Dewar only.
Ray et al. (1996)	77 K	DC-DC	Si MOSFET	PWM Boost	24 VDC	48 VDC	150 W	50 kHz	Efficiency improvement from 94% to 95.9%	Compared difference between HTS and MPP core-based inductor.
Perez-Guerrero et al. (1997, 1999)	77 K	DC-DC	Si MOSFET	Three level Buck	48 VDC	12 VDC	60 W	50 kHz	87.27% efficient at cold temperature	Power and control circuit, filter inductors and capacitors inside Dewar.
Elbuluk et al. (2000) and Gerber et al. (2000)	83 K	DC-DC	N/A	Buck	9-75 VDC	3.3-5 VDC	8-13 W	Variable	Variable efficiencies based upon converter manufacturers	Comparison of numerous converters from different manufacturers.
Elbuluk et al. (2002)	133 K	DC-DC	Commercial converter module	Buck	16-40 VDC	3.3 VDC	10 W	N/A	Variable efficiencies based upon converter loading	Investigation of a commercial module under different loading and temperatures.
Li et al. (2005)	77 K	DC-DC	Si MOSFET	Boost	N/A	N/A	N/A	N/A	N/A	Performance comparison between hard switching and soft switching.

Table 4 Summary of different converters for cryogenic applications (continued)

Ref.	*Lowest temperature*	*Type*	*Device*	*Topology*	*Input voltage*	*Output voltage*	*Power*	*Switching frequency*	*Efficiency*	*Comments*
Jia and Forsyth (2006)	20 K	DC-DC	Si MOSFET, Si/SiC Schottky diodes	Buck	120 VDC	60 VDC	500 W	50 kHz	N/A	Extended goal of integrating converter with superconducting machine.
Bourne et al. (2008) and Garrett et al. (2007)	89 K	DC Motor Drive	Si, SiGe, GaN, GaAs	Full bridge	28 VDC	24 VDC	20 W	N/A	N/A	PM DC motor was run by a full bridge stage
Chen et al. (2016)	77 K	DC-DC	CoolMOS MOSFETs	Synchronous Boost	200 VDC	400 VDC	40 kW	400 Hz	N/A	Integrates two cryogenic MOSFETs and one HTS inductor
Wang et al. (2019)	Room temperature testing only	DC-AC	SiC MOSFETs	3L-ANPC	± 500 VDC	600 V RMS @ 3 kHz	1 MW	70 kHz with SVM	N/A	Only room temperature testing carried out
Barth et al. (2017, 2020)	133 K	DC-AC	GaN FETs 200 V	Flying capacitor 3L	150 VDC	45 V RMS @ 60 Hz	1 kW, 1 Ø	120 kHz	Peak value of 96.7	Ceramic capacitors
Gui et al. (2019b)	Not reported	DC-AC	Si MOSFETs	3L-ANPC	1 kVDC	600 V RMS @ 3 kHz	40 kW	140 kHz	97.8% at full load at cryogenic temperature	Packaging and integration of the inverter designed.

From the review of converters, it can be observed that converters designed for CT have low power ratings and lower switching frequencies. Considering the device performance, Si based devices is used in most of the designs whereas GaN based devices are used in only one of the converters discussed. From the perspective of passive components, polypropylene film capacitors and powdered cores are utilised most of the time. A detailed summary of power ratings, switching frequency, device type, efficiency, and the nature of the converter is presented in Table 4.

4 Cryogenic machines

No actualised and finally optimised motor design for CTs with aviation applications has been developed, yet. Haran et al. (2017) provided the overview table of superconducting machines designed practically, and conceptually for aviation applications. Moreover, the developments that are beneficial for cryogenic motors/generators in applications other than aviation like submarines, wind turbines, and ships propulsion system are considered where benefits for high density, high efficiency super conducting machines can be achieved. In this paper, the recent studies of CT operating machines are gathered on top of a review paper for superconducting machines. The bottle neck for commercially developed cryogenic machines using superconductors integrated with motor/generators is their cost. The trade-off between the low temperature operation of superconducting machines with the cryocooler system size and cost should be resolved. Also, the utilisation risk is higher while using cryogenic machines as they are not fully tested in different ranges of power and environmental situations. In this way, CT machines are not a reliable choice compared to conventional machines and more practice is required in this area.

4.1 AC losses

Since a cryogenic motor’s performance and behaviour depends on the cooling medium used to achieve the low temperature environment, a detailed study is required on cryogenic machines. The superconductors used for cryogenic machines helps to achieve high power density as the resistive losses are low. However due to the high electrical conductivity, the AC losses are higher and make it an overall inefficient choice. Then, one prominent point in developing cryogenic machines is to limit the AC losses as much as possible. In this regard, Haran et al. (2017) proposed a development path for the superconductors. High efficiency and high-density machines can be achieved by using superconductors possessing low losses in both field and armature windings due to lower resistivity. However, the AC losses are challenging. The cryogenic motors with higher power density are operating at higher speed, and Lv et al. (2019a) found their AC losses to be higher. The solutions to avoid these losses involve the relationship between superconducting material, core magnetic material choice, and the rotor and stator design. Lv et al. (2019b) studied different materials to calculate estimated loss for motors magnetic materials, including grain oriented and non-oriented silicon steel sheets and amorphous alloy strips. Magnetic density is almost the same for these materials. Then the hysteresis loss is the same. As eddy current losses are proportional to the electrical conductivity of the material, the total loss is increasing with conductivity. Generally, the conductivity of magnetic material in CT is 120% of that in RT. Besides, Haran et al.

(2017) suggested the windings to be litz/stranded conductors to further decrease the AC losses. Induction machines (IM) were not an appropriate choice before developing the superconductors with low AC losses, because both rotor and stator carry AC current in an induction machine. Therefore, building a high power (> 5000 hp) induction machine was not an efficient choice.

4.2 Permanent magnet synchronous machine (PMSM) design considerations

As synchronous machines are mostly used in higher power applications, the recent updates on PMSM cryogenic design are provided. Xu et al. (2019) presented a 100,000 RPM, 10.5 kW design for PMSM in which the PM material is selected to avoid thermal instability due to large eddy currents and wind friction losses of high frequency. Therefore, samarium-cobalt (Sm_2Co_{17}) is selected as a core material due to its higher curie temperature and maximum operation temperature. The rotor was selected to be two-pole to have a lower frequency machine, thereby lowering the iron losses of the motor while also lowering the switching losses of the driving converter. Also, a rotating sleeve was designed to protect the rotor as it cannot stand the high centrifugal forces induced in high frequency operation.

Lv et al. (2019a) presented a comparison between an integer slot winding and a fractional one for a PMSM. However, a slotless motor has lower amplitude high frequency tooth harmonic magnetic fields, as it has a smaller airgap magnetic density. To avoid high frequency losses, it is suggested to limit poles. It is illustrated that a fractional motor with the same characteristic of introducing similar back electromagnetic force (EMF), has lower cogging torque, smoother torque, and lower core loss due to the low amplitude of harmonics in comparison to the integer slot one.

4.3 Volume of the machine

As current density per slot area of the rotor and stator increases, the slot area of both can be decreased proportional to the increment in electrical conductivity. Therefore, the total volume of the motor can be decreased. However, Kim et al. (2017) found that torque will be the same at CT as at RT. Using superconductors, the magnetic field remanence introduces reduced back EMF in the magnetic core. Therefore, Guo et al. (2018a) proposed the PM volume should be designed to decrease proportional to magnetic field remanence in CT. On the other hand, the slot area decrement is necessary at CT as the low electrical resistivity of the material causes dynamic and steady state problems. Guo et al. (2018b) proposed a Sm_2Co_{17} core material to avoid this effect.

4.4 Indirect study

Testing and building different cryogenic machines is complicated and costly. Furthermore, a detailed study is not possible since cryogenic pump and immersed machine rotor share a common shaft. Different methods are presented in literature to achieve a good understanding of the running performance of the cryogenic machines. Ai et al. (2020a) presented the use of a Γ-equivalent circuit model by transferring the parameters of the rotor part, which cannot be measured directly, to the stator part. It predicts the performance of the machine, current, output torque, power factor, and efficiency. The drawback is that the detailed predictions cannot be achieved using this method as detailed temperature modelling and relationships with electrical and mechanical parameters are not involved. Podlaski et al. (2020) implemented a multi domain model, with a co-simulation of electrical, mechanical, and thermal models, of the cryogenic system using Modelica software. In this modelling, the variables of transfer functions are simplified, components relations are considered in and multi domain system and parameters are prioritised to speed up the calculations. Ai et al. (2020b) simulated coupled electromagnetic and thermal analysis in MotorCAD. It is time saving to couple the finite element analysis (FEA) with a lumped circuit thermal network as opposed to modelling everything in FEA. Similarly, Barański and Szelag (2012) presented the coupled model of equations with FEA, including the nonlinearity of the magnetic material which gives distribution of the magnetic field and currents in windings. The modelling is done on IM and the output of that is the movement of rotor, skewed slots, and the influence of temperature on material characteristics.

5 Cryogenic cooling methods

Cryogenic cooling is concerned with operating temperatures below 100 K and is the enabling factor and key technology for cryogenic power electronics conversion. Numerous cooling solutions can enable varying or constant temperature environments for the characterisation and operation of cryogenic components (Meseguer et al., 2012). These solutions need not only be highly reliable, but also need to be high efficiency, low cost and smaller in size. Selection of a cryogenic cooling solution also depends on several other factors like steady state cooling needs, response to dynamic load, uniformity of temperature and availability of cryogens (Rajashekara and Akin, 2013). The cryogenic cooling power requirements are primarily dictated by the Carnot efficiency; depend on the unit power losses and the desired cryogenic temperature. As an example, 1 W of heat removal at LN_2 temperatures requires an 8 W–10 W cooling plant, whereas 800–1,000 W maybe required at LHe_2 temperature (Rajashekara and Akin, 2013). This not only affects the cooling cost, but it affects the selection of a cryogenic plant as well.

Leaving aside radiators, cryogenic coolers/systems can broadly be described as open cycle refrigerators, and closed cycle refrigerators (Meseguer et al., 2012). Open cycle refrigerators use stored cryogens, either solid or liquid (for example LN_2, LH_2 and LHe_2). In an open cycle system, the cold heat sink is generated by the evaporation of cryogenic materials, i.e., sublimation of a solid, or the boiling of a liquid, and there is no heat radiation. Therefore, this is an example of a passive system, and the stored cryogenic material and heat leakages determine the overall system lifetime. On the contrary, mechanical coolers (also called as active coolers) are employed in closed cycle systems where work is continuously performed during operation. Closed cycle systems can primarily be categorised as:

a regenerative (oscillating flow)

b recuperative (steady flow)

c some hybrid of the two (Meseguer et al., 2012; Rajashekara and Akin, 2013).

Regenerative coolers consist of a compressor which generates a pressure wave and a cold finger using a regenerator. In this mechanism, heat is rejected when the gas compresses and extracted when the gas expands. Three main regenerative cycle cryocoolers are Stirling cycle, Gifford-McMahon (GM), and pulse tube refrigerators. Recuperative coolers are based on the enthalpy difference between high-and low-pressure gas. Joule-Thomson and Brayton cycle coolers are the two recuperative style coolers where the former is simpler, but less efficient (Rajashekara and Akin, 2013).

A summary of the pros and cons and typical operating temperatures with different cooling methods is presented in Table 5.

Table 5 Summary of different cooling methods

Cooling type	*Cryogen*	*Typical temperature (K)*	*Pros (Meseguer et al., 2012; Radebaugh, 2002; Rajashekara and Akin, 2013)*	*Cons (Meseguer et al., 2012; Radebaugh, 2002; Rajashekara and Akin, 2013)*
Open cycle coolers	LO_2	90.2	• Cost effective	• Passive thermal management
	LN_2	77.4	• Energy efficient	
	LH_2	20.3		
	LHe_2	4.2		
Closed cycle coolers	Regenerative coolers	4-77	• High efficiency • Small size • Cheap • Scalable	• Vibrations from the moving displacer
	Recuperative coolers	77	• Longer lifetime • Cold fluid over long distances	• Large heat exchanger • Expensive

6 Conclusions

Integrated cryogenic operation of superconducting machines and power electronics converters will be the basis of power conversion systems for modern transportation and deep space missions, as they offer higher power density and conversion efficiencies. Considering the improved performance of both machines and converters at lower temperatures, different constituent components of cryogenic power conversion systems are reviewed in this article. The review is essentially comprised of devices, passive components, converters, and superconducting machines. Since detailed reviews of devices and passive components have already been conducted, this paper serves to summarise the devices and passive component's part, while the focus is on reviewing different converter topologies, their power ratings, the types of devices used, the types of passive components incorporated, and the operating switching frequencies. The paper tabulated almost all the cryogenically cooled converters developed so far, with a summary of their specifications to serve as an easy reference. Also, the latest research and development challenge in designing and operating superconducting machines is presented. Since variation in the performance of the different components involved depends significantly on the operating temperature, this paper works to facilitate the design of cryogenic systems at various temperatures. This survey will help to flesh out the behaviour of such components and can serve as a database for the successful design of cryogenic power conversion systems.

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