Design and Testing of Isolated Gate Driver for Cryogenic Environments

Abdelrahman Elwakeel, *Student Member, IEEE*, Neville McNeill, Rafael Peña Alzola, Ravi Kiran Surapaneni, Gowtham Galla, Ludovic Ybanez, Min Zhang, *Member, IEEE*, Weijia Yuan, *Senior Member, IEEE*

***Abstract*— Aiming to increase the power density of electrical systems and realize all-electric aircraft, research has been focused on immersing power electronics at cryogenic temperatures as they tend to have lower conduction and switching losses. To ensure proper switching of semiconductor devices at cryogenic temperature, their gate driver circuits should ideally be placed in close physical proximity and therefore in the same environment. Although some commercial off-the-shelf gate drivers have been tested at cryogenic temperatures, in this article we present a bespoke magnetically isolated gate driver for cryogenic temperatures. Experiments with the circuit immersed in liquid nitrogen verify the proposals of the article.**

***Index Terms*—Cryogenic electronics, gate driver, IGBT, MOSFET, propulsion**

I. INTRODUCTION

THE aviation industry is striving to achieve zero emissions to comply with the strict emission laws set by governments globally. In response, Airbus is actively developing the ZEROe, an aircraft powered by hydrogen, with the goal of making it ready for flight by 2035 [1]. The power source of the aircraft would depend on the distance and the number of passengers; a) for short-haul flights, lithium-ion batteries would be used for passenger numbers less than 70 [2], b) hydrogen fuel cells would be used for longer-distance flights as they have a higher power density than batteries [3]. In the hydrogen aircraft architecture presented in [3], superconducting motors and cryogenic power electronics increase the system's power density. The power electronics is aimed to be working at temperature range higher than hydrogen to prevent carrier freeze-out. Research has been done on designing power converters suitable to be used at temperatures of 123 K and below [4]-[6]. To drive such a converter, the distance between the gate driver circuits and the power semiconductor devices should be minimal to avoid oscillations and susceptibility to noise. Figure 1 shows the implementation of a cryogenic system with a fuel cell [3], where gate drivers need to be situated within the cold temperature region to minimize the distance to the switching devices.

Gate drivers mainly consist of two parts: 1) signal transmission and 2) auxiliary power supply. Commercial off-the-shelf gate drivers have been tested at cryogenic temperatures [7]-[9], where three different gate driver ICs that use capacitively-coupled signal isolation have been immersed in a cryogenic liquid. Two of these were found to not function below 90 K [8]. Magnetic signal isolation can be more reliable at cryogenic temperature as it involves less complicated circuitry with more robust components [8]. However, there is a research gap in finding inductive isolated gate drivers at cryogenic temperature as most commercial drivers use ferrite cores which have a reduced permeability and increased losses at lower temperatures. In [8], different types of commercial off-the-shelf auxiliary power supplies for gate drivers were tested at cryogenic temperatures. The results have shown that either they fail or suffer from a reduction in output voltage. This presents another research gap in developing a cryogenic power supply for the gate driver for IGBTs/MOSFETs.

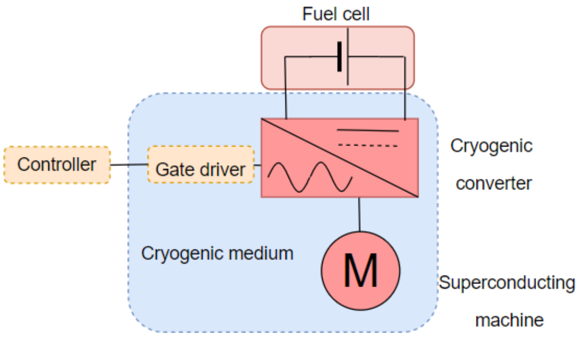


Fig. 1. Gate driver design for cryogenic temperature.

The novelty of this article can be summarized into two main points; 1) designing a reliable gate driver that uses magnetic signal isolation and 2) developing a reliable power supply for the gate driver, both of which can operate over a wide temperature range between 77 K and 300 K. The full design and the testing of a magnetically isolated gate driver are presented

---

Corresponding author: Abdelrahman Elwakeel

Abdelrahman El-Wakeel, Neville McNeill, Rafael Peña Alzola, Min Zhang and Weijia Yuan are with the Department of Electronic and Electrical Engineering, University of Strathclyde Glasgow, UK, G1 1XQ.

(email:Abdelrahman.Elwakeel@Strath.ac.uk,Neville.Mcneill@strath.ac.uk , Rafael.Pena-Alzola@strath.ac.uk,Min.Zhang@strath.ac.uk, Weijia.Yuan@Strath.ac.uk)

Ravi Kiran Surapaneni, Gowtham Galla, Ludovic Ybanez are with Airbus UpNext ,Rue des beaux avions,31700, France.

(e-mail: Ravi-Kiran.Surapaneni@Airbus.com, Gowtham.Galla@Airbus.com, Ludovic.Ybanez@Airbus.com)

This work is part supported by Airbus UpNext

in this article. Section II gives a short literature review of candidate components and devices for the gate driver. Section III presents the design of the gate driver. Section IV presents the experimental results of testing the gate driver at cryogenic and room temperatures.

II. LITERATURE REVIEW ON DEVICE PERFORMANCES AT CRYOGENIC TEMPERATURES

Magnetically isolated gate driver circuits are mainly constructed of; 1) logic circuits; for signal processing 2) the auxiliary power supply; to provide the power consumed in driving the switch 3) magnetic cores; for inductive isolation, and 4) capacitors for filtering. In this section, the literature on testing each of these components is reviewed to assist with the circuit design in Section III.

A. Performance of Logic Circuits at Cryogenic Temperature

The performance of control circuits has been assessed at temperatures between 110 K to 300 K in [9]-[14], where different types of control IC were tested. The experimental results showed that CMOS (complementary metal-oxide-semiconductor) devices have robust and consistent performance as the temperature decreases. In [12] four ICs were tested, where the two bipolar technology ICs did not work below 130 K. One BiCMOS (Bipolar CMOS) IC was able to function below 100 K. The study also showed that the bipolar technology ICs exhibited large noise when operated at cryogenic temperature. The same results were shown in [13] where the bipolar-based IC ceased operating at below 163 K. However, these ICs will readily recover and commence working once their temperature rises again. The CMOS-based IC tested in [14] was able to operate down to 88 K.

B. Performance of Magnetic Core Materials at Cryogenic Temperatures

Various magnetic core materials were assessed at cryogenic temperatures in [15]-[17]. The ferrite cores which are commonly used in room-temperature gate drivers are found not to be suitable for the cryogenic temperature application. However, Nano-crystalline and amorphous cores were deemed suitable as their permeabilities, and losses did not change as significantly with the decrease in temperature.

C. Performance of Capacitors at Cryogenic Temperatures

Different types of capacitors have been tested at cryogenic temperatures [18]-[22]. Both electrolytic and ceramic capacitors, which are commonly used in gate driver circuits, have a decreased capacitance with a decrease in temperature. Conversely, the capacitances of polypropylene and tantalum capacitors remain almost the same and, thus, they are better candidates for the cryogenic gate driver.

D. Summary of the Literature Review

Based on the literature review we can deduce the following.

- CMOS devices can function at cryogenic temperatures. They are typically more resistant to radiation than bipolar devices, which makes them well-suited for use in space and other harsh environments.
- Nano-crystalline and amorphous cores are often used in transformer and inductor applications at cryogenic temperatures due to their high permeability and low core loss are not as adversely affected as is the case with ferrite materials.
- Polypropylene and film capacitors are also good choices for use in cryogenic circuits due to their stability and reliability at low temperatures.

III. DESIGN OF THE GATE DRIVER CIRCUIT

In this section, the design process for a cryogenic gate driver, is explained. This is done through two main parts.

- Identifying the system parameter and the application.
- By designing the sub-circuits of the gate driver; which include mainly, 1) voltage regulator (5 V), 2) signal conditioning, 3) gate driver power supply, and 4) the desaturation protection.

A. System Parameters

The specification of the gate driver is presented in Table I. The supply voltage to the driver is 12 V and the expected output is 20 V for high and – 10 V for low.

TABLE 1. SPECIFICATION OF THE GATE DRIVER

Symbol	Definition	Value
V_{in}	Input voltage	12V
V_{out}	Output voltage	20 V, -10 V
f_{sw}	Switching frequency	0-200 kHz

B. Circuit Design

Figure 2 depicts the architecture of an isolated gate driver featuring four distinct functional blocks, voltage regulator, signal conditioning, isolated power supply, and desaturation protection circuit. Below are the functions of each of the circuits.

1- Voltage regulator (5 V) (green box):

As the voltage supply for the gate driver is 12 V, the voltage regulator is used to ensure that voltage across the CMOS does not surpass its rated 5 V. Conventional series linear regulator LM7805 was found to fail when the temperature dropped to 77 K, which can be attributed to the BJT failure that is commonly known to happen at cryogenic temperatures. A simple Zener diode on the other hand has shown robustness at 77 K and thus is implemented in the circuit as shown in Fig 2.

2- Signal conditioning (blue box):

The signal conditioning structure is presented in the blue box shown in Fig. 2. The waveform going through the signal conditioning circuit is shown in the grey box. The input signal is a square waveform that is then processed through the oscillator circuit and logic gates to become a bipolar signal as shown in Fig. 2. The bipolar signal is then transmitted through the transformer and then rectified to recover the same waveform as the input signal.

3- Isolated power supply (orange box):

An isolated push-pull power supply is designed to feed the power of the gate driver circuit as shown in Fig. 2. The push-pull converter consists of three windings on the secondary side of a transformer, with one winding providing a positive voltage bias (20 V) and the other winding providing a negative voltage bias (- 10 V). The third winding is used to feed the desaturation protection.

4- Desaturation circuit protection (purple box):

To ensure short-circuit protection, a desaturation circuit has been incorporated, as depicted in Fig. 2. The circuit uses a comparator that monitors the collector-emitter voltage, and when it surpasses the predetermined threshold, it activates the fault signal.

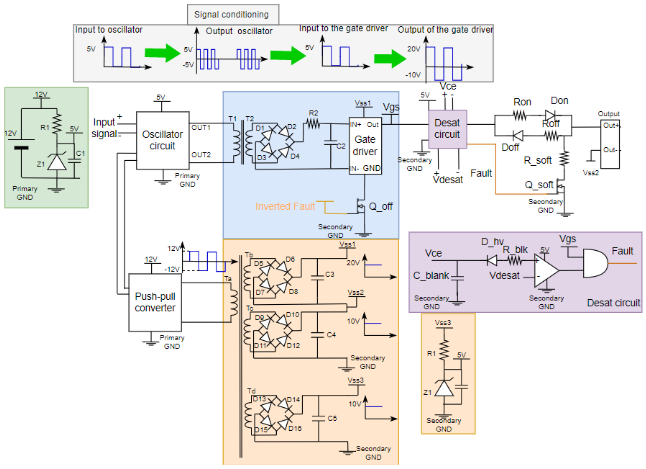


Fig. 2. Gate driver design for cryogenic temperature.

C. Selection of Devices

The selected devices are listed in Table II. The capacitors were all polypropylene as they have shown good performance at cryogenic temperatures. Similarly, nano-crystalline magnetic cores were selected as they have shown to be reliable at cryogenic temperatures. To confirm that the devices work appropriately at cryogenic temperatures they were tested separately. An IGBT was chosen as it was shown in the previous work [23] that of the semiconductors used at cryogenic temperature, IGBTs tend to perform better than SiC MOSFETs as they have lower switching losses and easy to parallel.

TABLE II. COMPONENTS OF THE CRYOGENIC GATE DRIVER

Device	Type	Part
Capacitors	Polypropylene	MKT1813
		PHE426HF7470JR06L2
Magnetic core	Nano-crystalline	T60006-L2020-W409
Logic circuits	CMOS	SN74F74N
		SN74AC00NE4
		IXDN614PI
Diodes	Signal diode	1N4148
	Zener diode	1N5231CTR
Test device	IGBT	CM800DX-24T1

For the selection of the most appropriate gate driver IC, two different devices were tested at cryogenic temperatures IXDN614PI and IXDN630YI. IXDN630YI has been shown to fail to operate at cryogenic temperatures. This was attributed to the bipolar circuitry within the device. However, the IXDN614PI device showed good performance as it does not contain bipolar circuitry and was thus used in the circuit.

IV. EXPERIMENTAL RESULTS

The gate driver circuit was designed and laid out on the PCB with robust IC that use through-hole packages. The circuit components listed in Table II were then assembled into the circuit shown in Fig. 3.

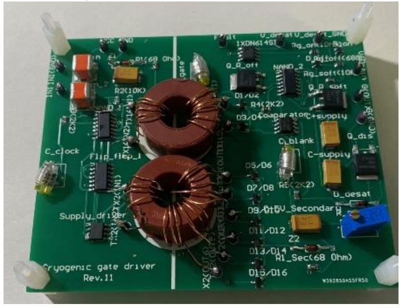
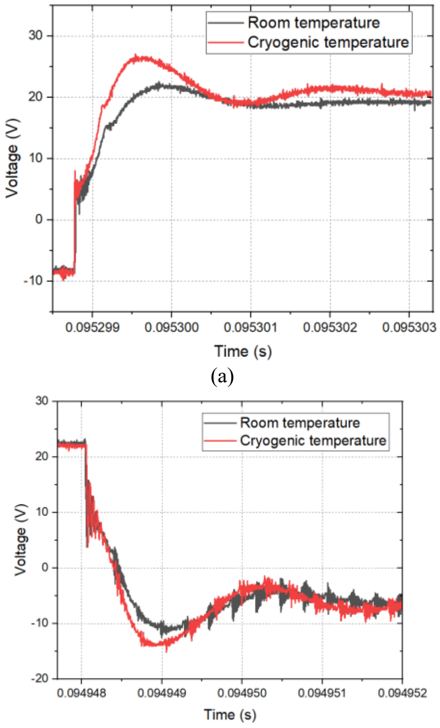


Fig. 3. Hardware design of the gate driver.

The gate driver integrated into the IGBT was tested twice, at room temperature and when immersed in liquid nitrogen. The rising and falling gate-emitter waveforms were recorded at room and cryogenic temperature, as shown in Figs. 4 and 5.



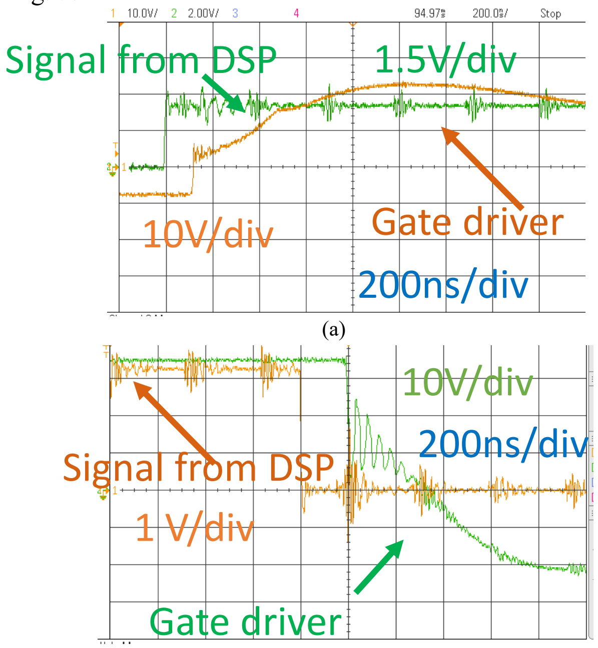
(a)

(b)

Fig. 4. (a) Gate-emitter voltage rising edge at room and cryogenic temperature, (b) Gate-emitter voltage falling edge at room and cryogenic temperature.

As presented in Figs. 4 (a) and (b), the gate driver has a larger peak output voltage (20 %) and a lower trough (-21 %) when at cryogenic temperature. This can be attributed to the increased efficiency of the push-pull power supply. In terms of oscillation, the gate driver is not affected by being immersed in liquid nitrogen. Figs. 4 (b) is slightly jittery due to the oscilloscopes bandwidths limitation of 200 MHz.

The turn-on propagation delay, the time taken by a signal to travel through the gate driver, was measured at room and cryogenic temperature and was found to remain virtually unaffected by the drop in the temperature. The propagation delay of the gate driver was measured at 400 ns as shown in Fig. 5.



(a)

(b)

Fig. 5. Waveforms showing propagation delays of the gate driver, (a) for turn-on, and (b) for turn-off.

A short-circuit test was run to determine the effectiveness of the desaturation circuit to switch off the device where the waveform is presented in Fig. 6. During the second waveform a short circuit was implemented across the device terminals which was sensed by the desaturation circuit triggering the soft-turn off mechanism of the IGBT. The driver's performance was assessed after 10 thermal cycles (cryo temp/normal temp) where the results showed that the cycling did not affect the circuit.

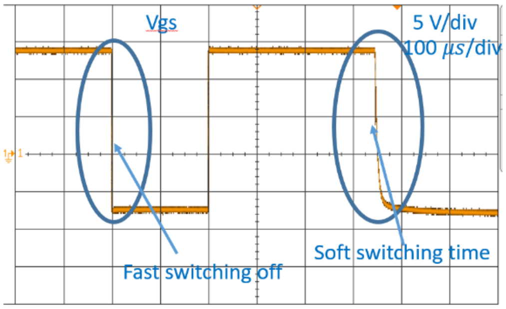


Fig.6: The waveform response triggered by a short circuit at the IGBT side desaturation circuit protection.

V. CONCLUSION

This letter presents a bespoke magnetically-isolated gate driver with a robust auxiliary power supply that can operate reliably at cryogenic temperatures. The proposed driver comprises ICs, magnetic cores, and desaturation protection that shows consistent performance at various temperatures. To validate the performance of the driver, it was connected to an IGBT, and tested at 77K. For future work, the gate driver would be tested at cryogenic temperature for the double pulse test and a full three-phase inverter.

ACKNOWLEDGMENT

This work is partly funded by Airbus UpNext.

REFERENCES

[1] "Zeroe," Airbus, Accessed: Feb. 3, 2024. [online]. Avaliable: https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe.

[2] T. Bærheim, J. J. Lamb, J. K. Nøland, and O. S. Burheim, "Potential and limitations of battery-powered all-electric regional flights–a Norwegian case study," *IEEE Trans. Transp. Elect.*, Aug. 2022.

[3] J. K. Nøland, "Hydrogen Electric Airplanes: A disruptive technological path to clean up the aviation sector," *IEEE Elect. Magazine*, vol. 9, no. 1, pp. 92-102, Mar. 2021.

[4] K. Rajashekara and B. Akin, "A review of cryogenic power electronics - status and applications," in *Proc., Int. Electric Machines Drives Conf.*, Chicago, Illinois, USA, pp. 899-904, May 2013.

[5] H. Gui *et al.*, "Review of power electronics components at cryogenic temperatures," *IEEE Trans. Power Electron.*, vol. 35, no. 5, pp. 5144-5156, May 2020.

[6] A. Elwakeel, Z. Feng, N. McNeill, M. Zhang, B. Williams, and W. Yuan, "Study of Power devices for use in phase-leg at cryogenic temperature," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1-5, Aug. 2021.

[7] Mustafeez-ul-Hassan, Y. Wu, V. Solovyov and F. Luo, "Investigation about operation and performance of gate drivers for power electronics converters for cryogenic temperatures," in *Proc., 24th European Conf. Power Electron. Appl.*, Hanover, Germany, pp. 1-9, Oct. 2022,

[8] Mustafeez–ul–Hassan, Y. Wu, V. Solovyov, and F. Luo, "Liquid nitrogen immersed and noise tolerant gate driver for cryogenically cooled power electronics applications," in *Proc., IEEE Appl. Power Electron. Conf. Expo.* TX, USA, pp. 555-561, May 2022.

[9] Y. Wei, M. M. Hossain, R. Sweeting, and A. Mantooth, "Functionality and performance evaluation of gate drivers under cryogenic temperature," in *Proc., IEEE Aerospace Conf.* MT, USA, pp. 1-9, Jun. 2021.

[10] M. E. Elbuluk, A. Hammoud, S. Gerber, R. Patterson, and E. Overton, "Performance of high-speed PWM control chips at cryogenic temperatures," *IEEE Trans. Ind. Appl.*, vol. 39, no. 2, pp. 443–450, Mar. 2003.

[11] M. Elbuluk, A. Hammoud, and R. Patterson, "Power electronic components, circuits and systems for deep space missions," in *Proc., IEEE 36th Power Electron. Specialists Conf.*, pp. 1156-1162. Mar. 2005.

[12] Bourne, R. Schupbach, B. Hollosi, J. Di, A. Lostetter, and H. A. Mantooth, "Ultra-wide temperature (-230 °C to 130 °C) dc-motor drive with SiGe asynchronous controller," in *Proc., IEEE Aerosp. Conf.,* pp. 1-15, May 2008.

[13] K. K. Leong, A. T. Bryant, and P. A. Mawby, "Power MOSFET operation at cryogenic temperatures: Comparison between HEXFET®, MDMeshTM and CoolMOSTM," in *Proc., 22nd Int. Symp. on Power Semiconductor Devices & IC's*, pp. 209-212, Aug. 2010.

[14] M. Elbuluk, A. Hammoud and R. Patterson, "Power electronic components, circuits and systems for deep space missions," in *Proc., IEEE 36th Power Electron. Specialists Conf.*, pp. 1156-1162. Mar. 2005.

[15] S. S. Gerber, "Performance of high-frequency high-flux magnetic cores at cryogenic temperatures," IECEC '02. 2002 37th Intersociety Energy Conversion Engineering Conference, 2002., Washington, DC, USA, 2002, pp. 249-254.

[16] S. Yin *et al.*, "Characterization of inductor magnetic cores for cryogenic applications," in *Proc., IEEE Energy Conversion Congr. Expo.*, pp. 5327-5333, Nov. 2021.

[17] X. Pei, A. C. Smith, L. Vandenbossche, and J. Rens, "Magnetic characterization of soft magnetic cores at cryogenic temperatures," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 5, pp. 1-6, Aug. 2019.

[18] Mantooth, "Development of a dc motor drive for extreme cold environments," in *Proc., IEEE 2007 Aerosp. Conf. Proc.*, pp. 1-12, Jun. 2007.

[19] Bourne, R. Schupbach, B. Hollosi, J. Di, A. Lostetter, and H. A. Mantooth, "Ultra-wide temperature (-230 °C to 130 °C) dc-motor drive with SiGe asynchronous controller," *IEEE Aerosp. Conf. Proc.* pp. 1-15, May 2008.

[20] M. J. Pan, "Performance of capacitors under dc bias at liquid nitrogen temperature," Cryogenics (Guildf)., vol. 45, no. 6, pp. 463–467, Jun. 2005.

[21] A. Hammoud and E. Overton, “Low temperature characterization of ceramic and film power capacitors,” *Conf. Electr. Insul. and Dielectr. Phenom.* CA, USA, vol. 2, pp. 701–704, Oct. 1996.

[22] F. Teyssandier and D. Prêle, “Commercially available capacitors at cryogenic temperatures”, 9*th Int. Workshop Low Temperature Electron.,* Guaruja, Brazil, pp. 1-5, Jun. 2010.

[23] A. Elwakeel et al., "Characterizing Semiconductor Devices for All-Electric Aircraft," in IEEE Access, vol. 11, pp. 73490-73504, 2023.