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Gate driver design for cryogenically cooled power electronic converters

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***Abstract*— This paper explores the design and experimental validation of an isolated half-bridge DC-DC converter customized for cryogenic environments, addressing the challenges posed by extreme low temperatures. The selected topology, isolated half-bridge converter, maintains exceptional output voltage stability with a simple structure. In this paper, careful component selection to ensure stable performance at cryogenic environments is practiced. The performance of the designed isolated DC-DC converter and practical challenges are investigated experimentally at a cryogenic temperature.**

***Index Terms*—DC-DC converter, isolated gate driver, cryogenic power electronics, half-bridge converter, electric aircraft.**

I. INTRODUCTION

Cryogenic extreme low temperatures impose unique challenges to electronic systems, demanding innovative solutions to ensure reliable and efficient operation [1]. Challenges are lack of Off-The-Shelf (OTS) cryogenic compatible components especially Integrated Circuits (ICs) and reliability issues, which is a critical concern in applications such as electric aircraft [2].

Aiming at integrating subsystems in superconducting energy conversion systems, developing cryogenic power electronic converters becomes highly crucial [3]. Moreover, efficiency can be improved by employing Gallium Nitride (GaN) transistors or Si MOSFETs exhibiting substantial reductions in their on-resistance at cryogenic temperatures [4-6]. However, challenges persist with magnetic components [7-9] and gate driver circuits [10] at cryogenic temperatures, demanding further exploration of components selections and designs. Recent developments have seen the proposal of few cryogenic power converter designs, but they often utilize room temperature designed gate drive boards/components, limiting their practicality.

A 1-KW three-level converter using GaN transistors were implemented and tested at -140 °C [11]. Gate driver of the converter employed OTS isolated DC-DC converter IC. According to the authors experience with OTS DC-DC ICs, as most of them use BJTs in their circuits, cannot operate below -150 °C.

In [12], a 3-KW buck converter was developed for cryogenic operations. However, only gate driver ICs with GaN devices were exposed to cryogenic environment and gate driver power was supplied from outside. A DC-DC converter was implemented for DC excitation of superconducting magnets [13]. In this work gate driver circuits were separated from cryogenic environment. A 20 KVA two-level current source inverter was implemented for cryogenic environments [14]. In this setup, both gate driver and power stage were placed at a cryogenic temperature. However, an OTS DC-DC converter IC was employed as a gate driver power supply unit. It was observed that all tested DC-DC converter ICs show inconsistent operation or significant reduction in their performance. In [15], a resonant converter is tested at a cryogenic temperature. In this work also a DC-DC converter IC was used to supply gate driver ICs. As the used DC-DC converter IC employs BJTs in its topology, the converter only operated up to 143K.

According to the literature, the lack of cryogenic suitable isolated power supply units is the biggest problem with the operation of gate drivers at cryogenic temperatures. Therefore, the objective of this research is to design, develop, and validate an isolated DC-DC converter tailored specifically for gate driver cryogenic operations. This paper contributes to the field by introducing an isolated DC-DC converter designed to operate seamlessly at cryogenic temperatures. To achieve this goal, the selection of an appropriate DC-DC converter topology for cryogenic environment and the careful consideration of cryogenic-compatible components are investigated in Section II of this paper. Experimental validations and practical challenges are elaborated in Section III.

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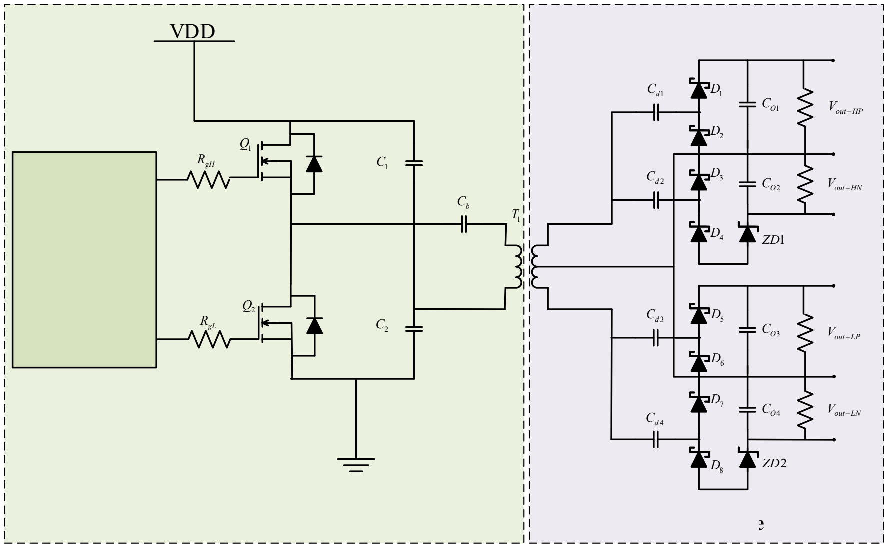

Figure 1. Schematic of the isolated half-bridge DC-DC converter

II. CONVERTER DESIGN CONSIDERATIONS FOR CERYOGENIC OPERATION

The objective of this converter design is to prototype and evaluate a technology demonstrator for an isolated DC-DC converter designed to operate at cryogenic temperatures, with the ultimate aim of deploying it as a power supply unit of gate driver circuits. Achieving this objective relies heavily on the careful choice of both the topology and components. This section will initially focus on the selection of the appropriate topology, followed by an exploration of the selection process for components compatible with cryogenic conditions.

A. Topology selection

Depending on how the B-H curve of the transformer core is used, isolated DC/DC converters can generally be divided into single-ended and double-ended topologies [16]. Double-ended topologies exploit both sides of transformer B-H curve by driving the transformer core in both opposite directions, ensuring the transformer core is used to its fullest and best potential.

Magnetic materials show variations in their hysteresis properties at cryogenic temperatures [17-19]. Double-ended topologies can help minimize the impact of hysteresis by symmetrically utilizing the B-H curve of the transformer core. As a result, magnetic behavior becomes more predictable and manageable, improving the overall system performance. Also, Eddy current losses, which occur due to the circulation of induced currents in conductive materials, can be reduced with a balanced double-ended topology. This eddy current loss reduction is of especial importance at cryogenic temperatures where due to increased conductivity eddy current losses tends to increase [20,21].

In line with the design objective, isolated half-bridge converter has been chosen among other double-ended topologies. This selection is underpinned by its well-established attributes, which include superior output voltage stability even under open-loop control, high efficiency, circuit simplicity, and suitability for gate drivers' power supply unit applications [22]. Considering challenges of cryogenic environments, an open-loop control approach is chosen for the designed isolated half-bridge converter. Adopting an open-loop control strategy simplifies the design and eliminates the need for the optocouplers and feedback circuits. This can improve stability and eliminate the negative impact of feedback circuit's altered behaviour at cryogenic temperatures.

Fig.1 shows schematic of the isolated half-bridge DC-DC converter. The topology consists of a half-bridge converter exciting a transformer with two secondary windings. The transformer's turn ratio is 3:2:2.

In the secondary side, aiming at achieving a high efficiency, Schottky diodes are employed for rectification forming voltage doubler circuits with associated capacitors. The half-bridge is driven by fixed switching frequency of 50 KHz at 50% duty cycle which remains unaffected by varying loads. This intentional choice of an open-loop control approach guarantees that the isolated DC/DC converter consistently operates under optimal conditions, allowing for seamless energy transfer from the primary to the secondary side of the transformer at cryogenic temperatures. Also, the output voltage only depends on the input voltage and the turns ratio of the transformer's windings.

B. Transformer

To achieve a compact size, a Power over Ethernet (PoE) transformer is employed. Characteristics of the used transformer in this design is listed in Table I. Material of the transformer core is high flux made from a 50% Nickel and 50% Iron alloy powder. High flux core materials are suitable for cryogenic applications exhibiting stable permeability and core loss at cryogenic temperatures compared to room temperature [23].

The transformer turn ratio can be used to compensate forward voltage of Schottky diodes in the secondary side rectification circuit. However, in this design, the desired output voltage can be achieved considering forward voltage of two Schottky diodes. For each output channel, output voltage must be +7 V and -3 V as the target application is to provide isolated bipolar voltage for GaN transistors gate driver. Input voltage is 12 V and transformer turn ration is 3:2:2. Therefore, voltage across each of transformer secondary windings is 4 V. Through the rectification the voltage across each positive output terminals (A_H-B_H and A_L-B_L) is as follows:

$$V_{out\_HP} = V_{out\_LP} = 2 \times V_s - 2 \times V_F \tag{1}$$

where, V_s is the transformer secondary winding voltage and V_F is forward voltage of Schottky diodes. Considering 500 mV voltage drop across each Schottky diode, V_{out} is +7V. For the negative voltage rail, a 4 V Zener diode in series is used to achieve -3 V. Therefore, voltage across each negative output terminals (B_H-C_H and B_L-C_L) is:

$$V_{out\_HP} = V_{out\_LP} = 2 \times V_s - V_Z - 2 \times V_F \tag{2}$$

where V_Z is the Zener voltage of ZD_1 and ZD_2.

Apart from transformer's turn ration, finding a trade-off between switching frequency and the size of the employed transformer is critical. Lower switching frequencies reduces switching losses. The selected switching frequency of 50 kHz aligns with this principle. However, lowering the switching frequency extends the duration of each switching cycle, allowing more time for energy to accumulate in the transformer's magnetic core. As a result, if the V-s limit is exceeded, transformer core saturates leading to excessive losses, and potential damage to the transformer.

The voltage-stress (V-s) experienced by the transformer during one switching cycle can be calculated as:

$$V - s_{min} = \frac{V_{DD}}{2} \times D \times T_{sw} \tag{3}$$

where $V\text{-}s_{min}$ is the minimum required V-s in (V×second), V_{DD} is the input voltage of the half-bridge, D is duty cycle of the half-bridge, and T_{sw} is the switching period.

In this design, the transformer's V-s limit is 80 V.µs MAX. Considering 12V supply voltage at 50 KHz switching frequency, V-s does not exceed the transformer's specified V-s limit.

C. Self-oscillating gate driver

Self-oscillating gate driver ICs can generate gate drive signals without the need for an external oscillator or controller through their built-in oscillator which simplifies the gate drive circuit design making it suitable for applications with fixed switching frequency and duty cycle.

Several self-oscillating gate driver ICs were tested at both room and cryogenic temperature and their behavior studied. Among the various ICs evaluated, it was observed that the FAN7387, manufactured by Onsemi, exhibited notably persistent and dependable performance under cryogenic conditions. Table II summarizes a list of evaluated self-oscillating gate driver ICs and their performance at cryogenic temperatures. For each IC, several tests with various oscillating frequencies were implemented in the range of 20 KHz to 200KHz and their performance consistency, oscillating frequency, and duty cycle generated gate signal were recorded. Except FAN7387 and L6571 other ICs were not functional at cryogenic temperature. In the case of FAN7387 and L6571, their oscillating frequency at cryogenic temperature did not change compared to their oscillating frequency at room temperature. However, for both ICs, duty cycle of the generated gate signal decreased slightly. It was observed that the variation in duty cycle increased with increasing oscillating frequency.

Table I. Transformer characteristics

Turn ratio	3:2:2
V-s limit	80 (V * µsec MAX)
Isolation	2500 V_{rms}
Dimensions (L×W×H)	10mm × 8mm × 11mm

D. Capacitors

Generally, the capacitance of capacitors tends to decrease at cryogenic temperatures due to the variation in their dielectric constant [23]. Capacitors with NP0, polypropylene, polyphenylene sulfide (PPS), and tantalum dielectric function well at cryogenic temperatures in terms of capacitance variation. To maintain consistent capacitance values, in this design, a combination of ceramic capacitors with NP0 dielectric and Tantalum capacitors are used. Since tantalum capacitors have a high capacitance density, this type of capacitor is used for high capacitance capacitors in this design and for small capacitance values ceramic NP0 capacitors are employed.

E. Diodes

To improve the efficiency, Schottkey diodes are used in the secondary side. Forward voltage of Schottky diodes slightly increases at cryogenic temperatures [23]. According to (1) and (2), this can reduce the amplitude of the DC-DC converter output voltage and needs to be taken into account in the design stage by selecting diodes with appropriate forward voltages. The voltage stress experienced by each diode in the secondary rectification circuit corresponds to the output voltage (V_{out_P}) during the period when the respective diode operates in a reverse-biased state, along with the forward voltage of corresponding diode within the voltage doubler circuit. For example, the voltage stress across D_2 when reverse biased can be expressed as:

$$V_{R\_D2} > V_{out-P} + V_{F\_D1} \tag{4}$$

where, V_{R_D2} is the voltage across D_2 when it is reverse biased and V_{F_D1} is the forward voltage of D_1.

As the converter circuit in the secondary side is symmetrical, the same equation applies to all rectifier diodes in the voltage doubler circuit.

F. Switches

As part of isolated DC-DC converter design for cryogenic environments, exploring the performance of semiconductor switches at cryogenic temperatures is essential. According to the Authors experience of testing several OTS isolated DC-

Table II. Summary of self-oscillating gate drivers performance at cryogenic temperature

Part number	manufacturer	Switching frequency range at room temperature	Switching frequency range at cryogenic temperature	Frequency variation at cryogenic temperature	Duty cycle variation at cryogenic temperature
IR2153	International rectifier	Up to 1 MHz	Stopped working	—	—
IR2085	International rectifier	Up to 500 KHz	Stopped working	—	—
IR25603	International rectifier	Up to 1 MHz	Stopped working	—	—
AUIR2085	International rectifier	Up to 500 KHz	Stopped working	—	—
L6571	STMicroelectronics	Up to 200 KHz	Functional up to 50KHz	Keep constant	Decrease slightly
FAN7387	ON Semiconductor	Up to 650 KHz	Functional up to 100KHz	Keep constant	Decrease slightly

DC converter ICs, it was observed that ICs using BJTs failed operating at cryogenic temperatures. Unlike BJTs, MOSFETs are unipolar conduction devices, which means they predominantly involve electron movement performing seamlessly at cryogenic temperatures. Si MOSFETs show superior performance at cryogenic temperatures over SiC MOSFETS and their on-resistance has positive temperature coefficient improving their performance at cryogenic temperatures. In this design two Si MOSFETs are used to form the half-bridge.

III. EXPERIMENTAL VALIDATION

Experimental validation tests for the designed DC-DC converter were conducted under cryogenic conditions within a liquid nitrogen environment. The results of these experimental validation tests can be used to prove the robustness and adaptability of the converter design in cryogenic environments.

A. Prototype and test setup

The designed isolated half-bridge DC-DC converter is prototyped using a four-layer PCB. Fig.2 shows the converter prototype. The setup for the isolated DC-DC converter at cryogenic temperature is shown in Fig. 3. For cryogenic temperature test the converter is submerged in liquid nitrogen that its temperature is -195 °C. A high bandwidth (30MHz) Rogowski coil probe was used for current measurements and two differential probes were used for voltage measurements. Input voltage of the converter is 12V supplied by a laboratory power supply unit. The converter is loaded from 0 to 300mA.

B. Experimental results

Fig.4 shows gate driver output signal at room and cryogenic temperatures. As can be seen at cryogenic temperature, duty cycle of the generated gate signal is reduced. Operating at cryogenic temperature, the behavior of self-oscillating gate driver in the half-bridge DC-DC converter shows an important phenomenon with respect to its generated gate signals. At cryogenic temperature, the gate signal exhibits a slightly smaller duty cycle compared to its counterpart at room temperature. At room temperature, the duty cycle typically was 0.5, thereby ensuring a consistent 100% power conversion within the half-bridge DC-DC converter throughout each switching interval.

However, as the temperature is reduced to cryogenic levels, the duty cycle shows a slight decrease, stabilizing at around 0.47. This reduction in duty cycle is important as it impacts the power conversion within the converter. In this scenario, a marginally lower duty cycle translates into a relative reduction in power conversion amount. The primary cause of this phenomenon can be attributed to the altered electrical characteristics of internal components of the self-oscillating gate driver at cryogenic temperatures influencing timing and duration of the gate signals generated by the self-oscillating driver.

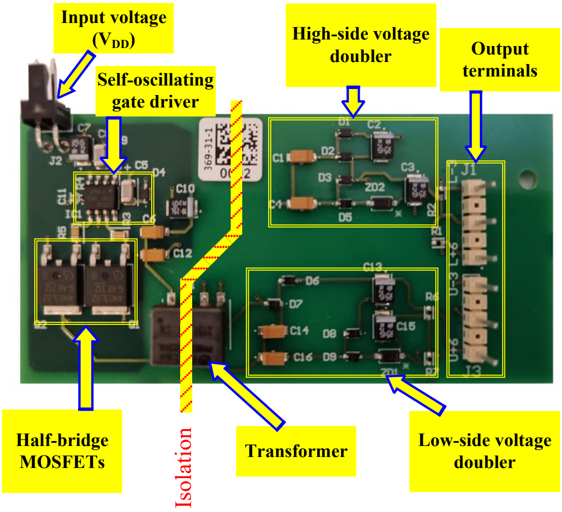

Figure 2. Isolated half-bridge DC-DC converter prototype

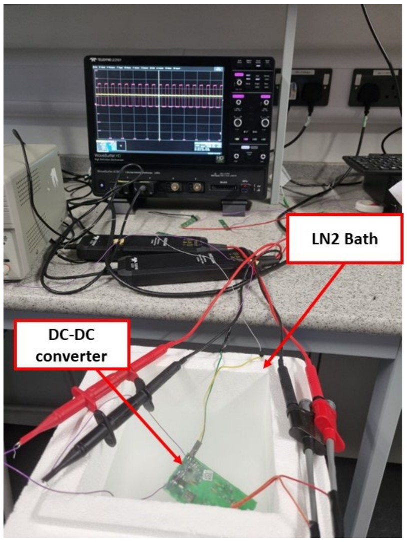

Figure 3. Experimental setup consisting of a LN2 bath, Power supply, oscilloscope, and designed isolated half-bridge DC-DC converter prototype.

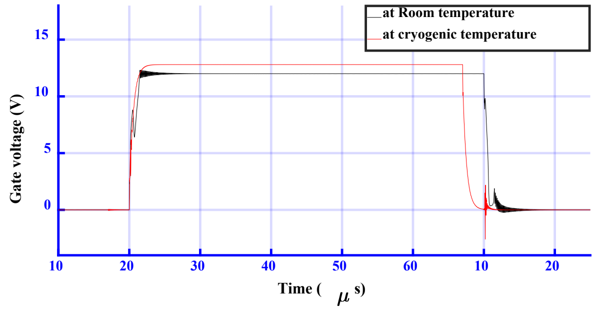

Figure 4. Gate signal generated by the self-oscillating gate driver at room temperature versus LN$_2$ temperature.

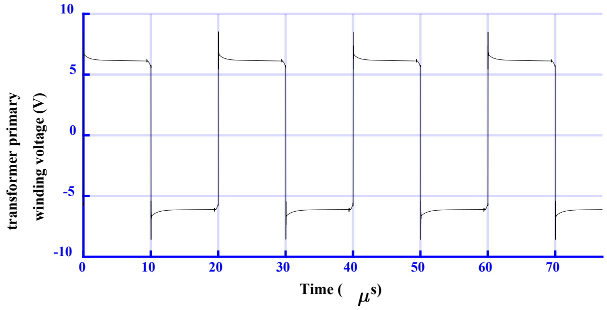

Figure 5. Voltage across the transformer primary winding.

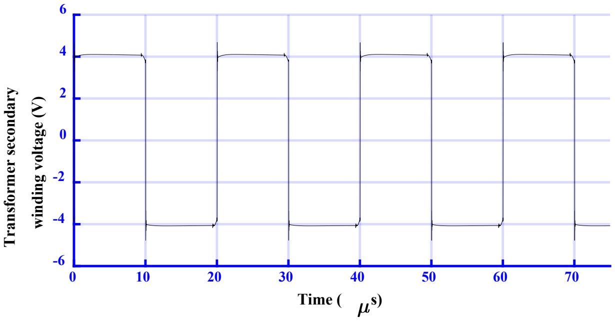

Figure 6. Voltage across the transformer secondary winding.

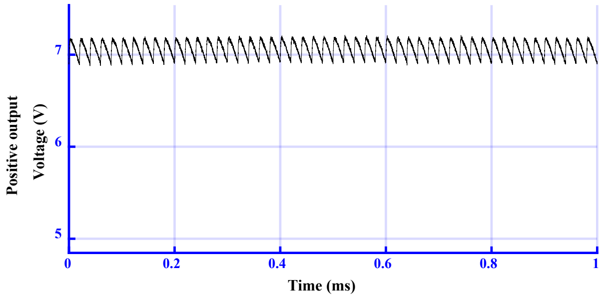

Figure 7 Positive output voltage.

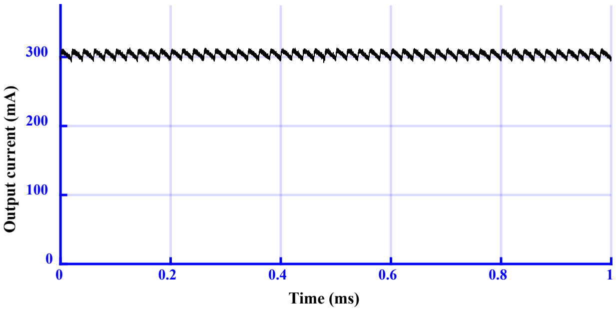

Figure 8. Positive output terminal load current.

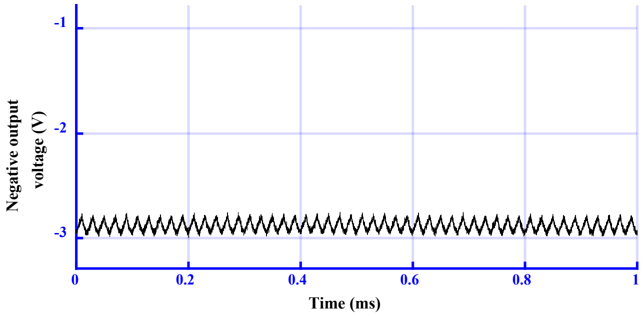

Figure 9. Negative output voltage.

Consequently, the slightly decreased duty cycle reduces the amount of energy transferred within each switching cycle, resulting in a decrease in the output voltage of the DC-DC converter. Under this condition, the output voltage of the converter can be calibrated through transformer turn ratio or input voltage regulation when designing converters for cryogenic environments. In this design, the input voltage of the DC-DC converter is increased from 12 V at room temperature to 12.8 V at cryogenic temperature to achieve desired +7 V and -3 V at output terminals and compensate voltage reduction imposed by decreased duty cycle and increased forward voltage of Schottky diodes in voltage doubler circuits.

Voltage across the transformer primary and secondary windings are shown in Fig.5 and Fig.6, respectively. Figures 7 and 8 show positive voltage and load current of the DC-DC converter, respectively. As can be seen, at 300mA load (2W output power), output voltage is well regulated. Fig.9 shows negative output voltage of the converter. Due to the increase Zener voltage of Zener diodes, negative output voltage is slightly lower than -3 V. This can be regulated by replacing the Zener diode with a Zener diode with smaller Zener voltage.

IV. CONCLUSION

Detailed design and experimental validation of a cryogenic isolated DC-DC converter are presented in this paper. The chosen double-ended topology, the isolated half-bridge converter, demonstrated superior output voltage stability, achieving levels of +7 V and -3 V under cryogenic conditions. The calibration and choice of components were done accurately employing ceramic and tantalum capacitors, Schottky diodes, and Si MOSFETs to showcase a reliable performance at extreme cryogenic temperatures. A self-oscillating gate driver IC consistently performed well under cryogenic conditions.

Experimental validation tests within a liquid nitrogen environment provided critical insights. The observed reduction in gate signal duty cycle at cryogenic temperatures, stabilized at approximately 0.47, demonstrated the converter's sensitivity to temperature variations. This phenomenon, attributed to altered electrical characteristics of components, highlights the importance of comprehensive component selection for cryogenic applications. In conclusion, this research has demonstrated the adaptability and robustness of the isolated half-bridge DC-DC converter for cryogenic environments. The promising results obtained, including stable and regulated output voltages, show its potential in cryogenic applications.

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