Experimental Evaluation of Cryogenic Performances of Electronic Components for Signal Isolation in Medium Voltage Power Converters

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***Abstract*— Operating power converters at cryogenic temperature (<-153^{0}C) can improve efficiency and power density. However, the reliable operation of power converters depends on satisfactory performance of all critical components at cryogenic temperature. While most of the critical components have been studied at cryogenic temperatures, some electronic components necessary for electrical isolation in signal circuits of a medium voltage power converter are yet to be evaluated extensively. This work studies the cryogenic performance of isolated auxiliary power supplies (APS), digital isolators, fiber optics, and isolation amplifiers to identify the well-performing candidates and to investigate the possible reason of failures at cryogenic temperatures. It is observed that some isolated APS with high isolation voltage and isolation amplifiers can work satisfactorily at cryogenic temperatures. The digital isolators are found to be more suitable for cryogenic operation than fiber optic links, even though the latter has better noise immunity.**

Keywords—cryogenic, isolator, fiber optics, isolated power supply, medium voltage, power converters, solid-state circuit breaker.

I. Introduction

Cryogenic application of power converters is receiving more attention in recent years due to the higher efficiency and power density it can offer in emerging applications like electric aircraft propulsion, space applications, superconducting machines etc. [1]. Many research studies have explored the cryogenic performances of critical components of a power converter such as different types of power semiconductor devices [2], inductors [3], capacitors [4], and gate drivers [5]. However, some essential components to provide necessary electrical isolation in the signal circuits of the power converters have received relatively low attention. Many high-power applications such as Electrified Aircraft Propulsion (EAP) systems require higher voltage isolation for the signal circuits of the power converters. This work supplements the existing knowledge with a detailed assessment of cryogenic performances of isolated auxiliary power supplies (APS), fiber optics, digital isolators, and isolation amplifiers, which are often used for gate driving, communication, and sensing in medium voltage converters.

The works presented in [6] and [7] found one and two isolated APSs respectively to be working well at cryogenic temperatures. However, the part numbers are not reported, making it difficult to use these results. The study in [8] found that only one converter (RV-0509S from RECOM with a voltage rating of 3kV) among seven isolated APSs performed satisfactorily at liquid Nitrogen temperature. Thus, a more detailed evaluation of the cryogenic performance of APSs with higher voltage isolation is needed for the cryogenic converter design.

In many applications, gate drive signals require digital isolator/fiber optic links to provide sufficient voltage isolation. Although an isolated gate driver can avoid the need for digital isolator, its isolation voltage may not be enough for some applications. A non-isolated driver may have better drive capability needed for some applications. Digital isolators are also essential to achieve digital signal communication with sufficient voltage isolation. For these applications, a digital isolator (ADuM5210) is tested in [9] and found to be performing well at cryogenic temperatures. However, more detailed study on digital isolators is missing. Similarly, there is a need for detailed evaluation of performance of fiber optic transmitter-receivers commonly used in medium voltage power electronic converters.

Sufficient voltage isolation is also critical for sending some of the sensed signals to the controller. Some sensors such as the current shunt or local voltage/temperature sensors need this voltage isolation to work. Sending analog signals with voltage isolation requires an isolation amplifier. A cryogenic performance evaluation of such amplifiers has not been reported in literatures.

The uncertainty of performance of these critical components along with gate drivers can cause the signal circuit to be placed away from the power circuit with thermal insulation between them [10], [11]. This configuration does not allow compact design and high power density and may need additional heating for the signal circuit. Hence, the critical components for the signal circuit isolation are tested in this work in a liquid Nitrogen based thermal chamber. The developed test boards and the test arrangements are shown in Fig. 1 and the results are explained in subsequent sections.

(a) (b)

(c)

Fig. 1. Developed test setup: (a) APS test board, (b) isolator, fiber optics, and isolation amplifier test board, (c) cryogenic test chamber with liquid Nitrogen cylinder.

II. Cryogenic Performance of Auxiliary Power Supplies

In power converters, the high-side gate divers require isolated power supply to operate. In case of low-voltage applications, non-isolated solution such as bootstrap gate driver may work satisfactorily. However, in case of medium and high voltage applications, it is essential to use auxiliary power supplies (APS) with short-term and continuous high voltage withstand capability as well as low isolation capacitance between two isolated sides. In this work, an application is considered where the isolation voltage requirement for the gate driver is 6.5 kV and a 12V to 12V isolated APS is required. Such high voltage requirement can be met with a single isolated APS or multiple isolated APSs connected in series. However, using multiple isolated APSs in series leads to larger size and weight and higher cost, as well as larger power dissipation for the gate drive circuit. On the other hand, the availability of the APS with isolation voltage higher than 6.5kV is limited.

Table I. Isolated auxiliary power supplies selected for test.

Part no	Vin (V)	Vout (V)	Power (W)	Isolation kV(60s)	Switch freq. (kHz)
REC3.5-1212S/R10	9-18	12	3.5	5	150-500
TIM3.5-1212	9-18	12	3.5	5	100
THM3-1212	9-18	12	3	5	135-165
JHL0312S12	10-17	12	3	4	250
MPP03-24S12WB	9-36	12	3	5	135-165
MTWA4-12S12	9-18	12	3	5	100
PWR1307AC	11-13	12	1.5	8	220

In this work, seven commercial off-the-shelf isolated APSs are selected based on their isolation voltage, voltage and power ratings, and availability. Maximum two isolated APSs will be used in series to achieve the required voltage isolation of 6.5kV. The ratings of these APSs are given in Table I. These APSs have the isolation voltage ratings of 4kV~8kV and power ratings of 1.5W~ 3.5W, suitable for gate driving applications. All the APSs are powered with 12V voltage source during the experiments. The 12V voltage source is not exposed to low temperature. The APSs are soldered on a PCB, as shown in Fig. 1(a) and placed in a thermal chamber capable of creating cryogenic temperatures down to -180^{0}C. The output voltages of the APSs are observed over a temperature range of -180^{0}C to 60^{0}C. As the temperature falls, some of the APSs start to perform poorly and/or failed. To determine the full capability of the APSs, they were tested with 10% and 80% load condition. The observed cryogenic performances of the APSs are shown in Fig. 2 (a) and (b) at 10% and 80% load, respectively.

The APSs start to lose the control over their output voltages at lower temperatures. All of them show some deviation of output voltage near -180^{0}C. The performance of an APS is considered here as satisfactory if the deviation of voltage is within 10% of the nominal voltage rating. It can be observed that all the APSs performed well over the entire temperature range at higher load (80%), but many of them failed at low load condition. This is expected as 15-25% of power is dissipated within an APS and this power loss at higher load is significantly large to keep its internal temperature higher. On the other hand, only three APSs REC3.5-1212S, MPP03-24S12, and PWR1307AC performed well at light load (10%) over the entire temperature range. Although the limited data is provided by manufacturers about the designs of these APSs, it can be noted from Table I that the APSs with lower switching frequency performed worse. A possible reason could be that these APSs may have used Bipolar Junction Transistors (BJTs), which are not suitable for high switching frequency and are known to perform poorly at cryogenic temperatures [2].

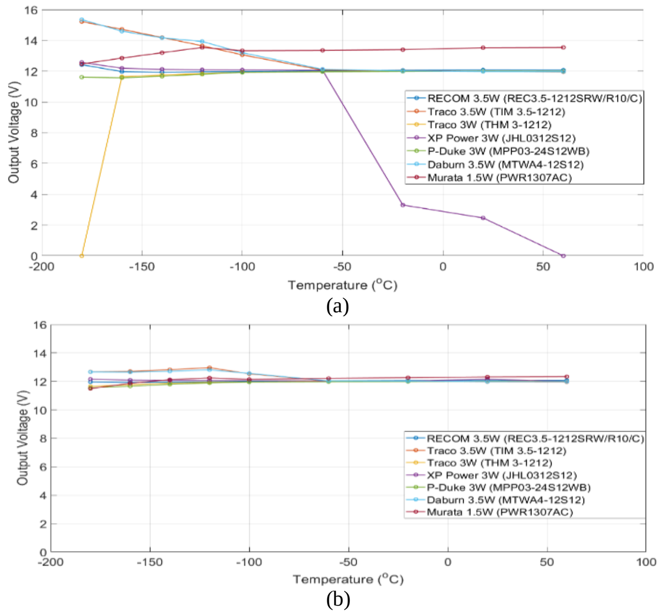


Fig. 2. Cryogenic test results for 12V isolated auxiliary power supplies: (a) 10% load, (b) 80% load.

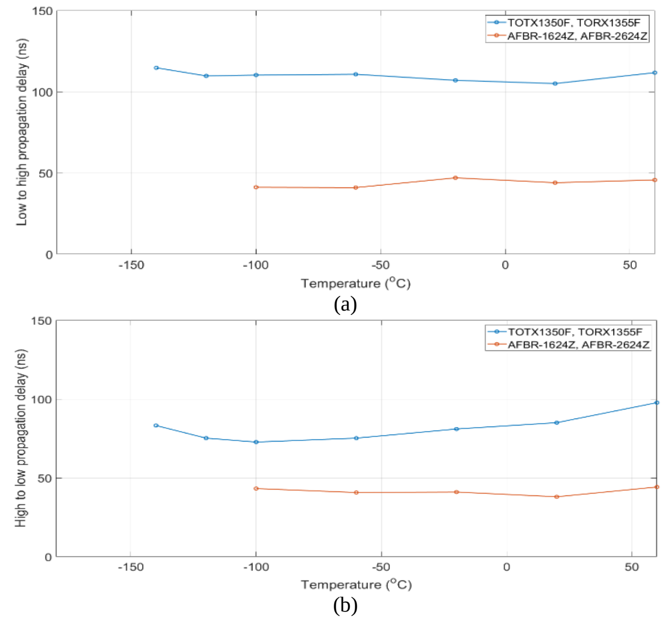


Fig. 3. The propagation delay of fiber-optic links during the low-high transition and high-low transition.

III. Cryogenic Performance of Fiber Optics

Fiber optics offer high voltage isolation and excellent noise immunity. Fiber optics links are often preferred in medium voltage applications. They are suitable for the application considered here that requires 6.5 kV voltage isolation. Thus, the cryogenic performance of commercial fiber optic links is of high interest and is evaluated here.

Two popular and commonly used fiber optic transmitter-receiver pairs, the AFBR series (AFBR-1624Z, AFBR-2624Z) from Broadcom and ToshLink series (TOTX1350F, TORX1355F) from Toshiba are selected to be tested for cryogenic applications. A 20 kHz square-wave pulse signal is sent to the fiber optic transmitters and the output signal of the receivers is observed. The output signal voltage level and high-low and low-high transitions are compared with the input signal. The performance of the fiber optic link is considered satisfactory if the output signal has expected voltage levels and does not have any significant distortion. The propagation delay is also measured compared to the input signal and plotted in Fig. 3. The test results reveal that the AFBR series offers a lower signal propagation delay but fails at -110^{0}C. On the other hand, the Toshlink transmitter-receiver pair has better temperature range and fails at -150^{0}C. Thus, the Toshlink series is more suitable for low temperature applications. However, none of them are suited for cryogenic temperatures (<-153^{0}C). Hence, if one of these is selected for a cryogenic power converter, extra efforts must be given to ensure that these components are placed away from the cold plate and has some thermal insulation.

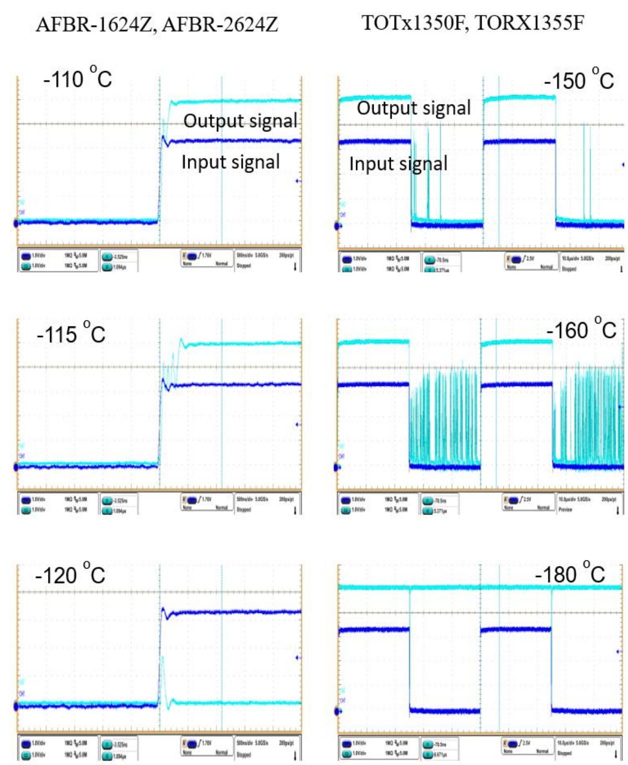


Fig. 4. Input and output signals of fiber optic receiver-transmitter pairs during failures.

The input and output signals of the fiber optic transmitter-receiver pairs during failures is shown in Fig. 4. It can be observed that the AFBR series start to show distorted output at -110^{0}C. The distortion increases further as the temperature drops. Finally, the output completely fails at -120^{0}C. It should be noted that the output becomes low when the component fails. This can help to avoid false turn-on of power devices in case of fiber-optic failure at cryogenic temperatures. On the other hand, the ToshLink series starts to show distortion in output signal at -150^{0}C. This distortion keeps increasing with temperature drop and a complete failure is observed near -180^{0}C. It should be noted that the output signal becomes high in case of a failure at the cryogenic temperature. This can be destructive for the power converter by causing false turn-on. A fast device protection must be installed if this fiber-optic link is selected.

The Toshlink receiver is based on CMOS, which performs better at cryogenic temperature compared to BJT-based TTL technology [12]. The AFBR receiver uses TTL circuit and hence it may be the cause of its poor performance.

IV. Cryogenic Performance of Digital Isolators

Digital isolators can be used instead of fiber optics links to send gate-drive signals to the high-side gate driver and to send/receive the digital communication, fault status, etc. The propagation delay of digital isolators is a critical parameter for reliable and fast communication between the controller and gate drivers. Five different digital isolators are selected in this work based on their low-propagation delays and availability. The propagation delays for these isolators are measured over the temperature range of -180^{0}C to 60^{0}C and plotted in Fig. 5.

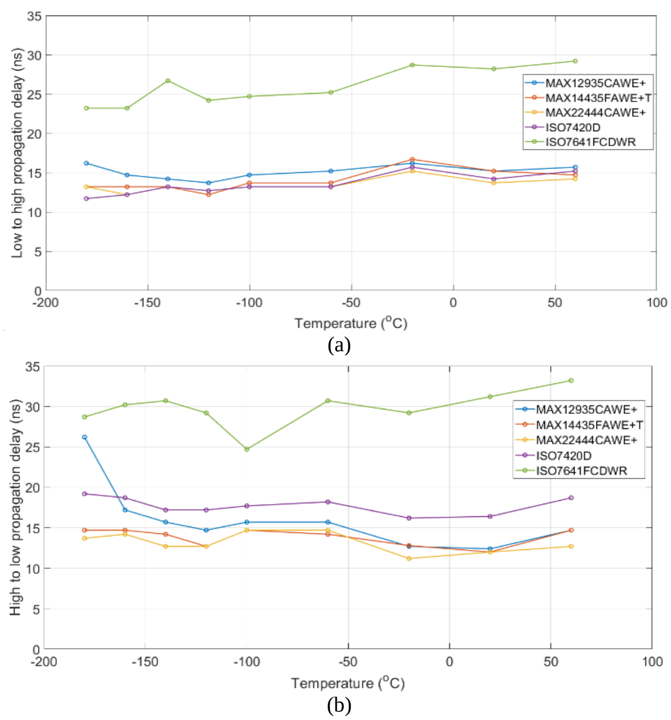


Fig. 5. Propagation delays of digital isolators during (a) low-high transition and (b) high-low transition.

It can be observed that all the digital isolators perform very well over the entire temperature range of tests. Therefore, the digital isolators are more reliable components for signal isolation at the cryogenic temperature.

Table II. Ratings of the selected digital isolators

Part no.	No. of channels	Isolation voltage	Maximum data rate
MAX12935CAWE+	2	5kVrms	200Mbps
MAX14435FAWE+T	4	5kVrms	200Mbps
MAX22444CAWE+	4	5kVrms	200Mbps
ISO7420D	2	2.5kVrms	1Mbps
ISO7641FCDWR	4	2.5kVrms	25Mbps

The ratings of the selected digital isolators are given in Table II. It can be noted from the table that none of the digital isolators has enough isolation voltage rating to meet the 6.5 kV isolation requirement considered in this work. Thus, we need to use two of them in series for sufficient voltage isolation, which however complicates the signal circuit. On the other hand, a single fiber optic link will be enough to achieve this voltage isolation. However, considering the cryogenic temperature operation a digital isolator will still be a better and more reliable choice.

V. Cryogenic Performance of Isolation Amplifiers

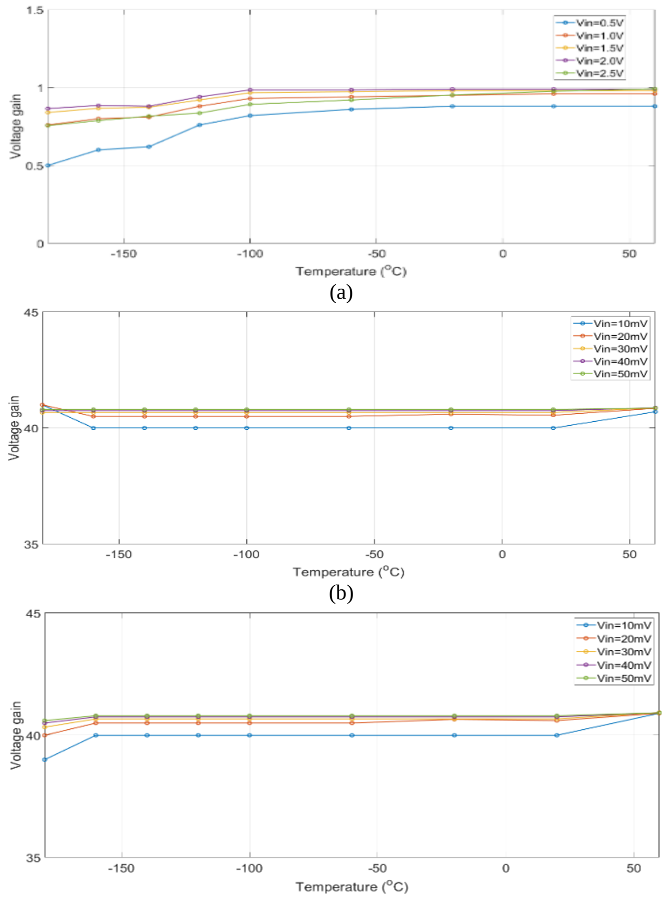
Isolation amplifier is necessary when there is a need to send analog signals such as sensor signals over a large voltage isolation to the controller. The performance and reliability of this amplifier is highly important as the integrity of the sensed signals is critical for reliable operations of the power converter. Ideally, the voltage gain of the isolation amplifier should not change with temperature variations.

Three isolation amplifiers are selected here to test their performance at cryogenic temperatures. The ratings of the selected isolation amplifiers are given in Table III. The output voltages of these amplifier are measured with the input signal varied over the entire allowed input range and their gains are observed under different temperatures down to -180^{0}C. In this test, only a variable dc voltage is used as the input signal of the amplifiers. It can be observed from Fig. 6 that the first amplifier (ADUM3190TRQZ) shows lower gain at lower temperatures. The other two amplifiers (AMC1202 and AMC1302) show very stable gains over the entire temperature range and can be used reliably for the analog signal isolation in cryogenic converters.

The ADUM3190 series use magnetic isolation and the AMC1202 and 1302 series use capacitive isolation. Possible degradation of magnetic core characteristics at cryogenic temperatures [3] may be the cause of the poor performance of ADUM3190.

Table III. Ratings of selected isolation amplifiers.

Part no.	No. of channels	Isolation voltage (kVrms)	Voltage gain	Input voltage range (V)
ADUM3190TRQZ	2	2.5	1	0.2-2.7
AMC1202	1	3.0	41	±0.05
AMC1302	1	5.0	41	±0.05



(a)
(b)
(c)

Fig. 6. Voltage gain of (a) ADUM3190TRQZ (gain = 1), (b) AMC1202DWVR (gain = 41), (c) AMC1302DWV (gain = 41).

VI. Conclusion

This work provides a comprehensive experimental evaluation of cryogenic performance of commercially available isolated auxiliary power supplies, digital isolators, fiber optic transmitter-receivers, and isolation amplifiers, which are commonly used components for the electrical isolation in the signal circuit of the power converter. Several isolated APSs, each rated for 4kV or more isolation voltage, digital isolators, and isolation amplifiers performed well over the entire temperature range from -180^{0}C to 60^{0}C. It is observed that APSs with higher switching frequencies and possibly using MOSFETS as switching devices perform better at cryogenic conditions. All the tested digital isolators and the capacitive isolation based isolation amplifiers performed satisfactorily over the entire temperature range. However, both of the commonly used fiber optic transmitter-receiver pairs failed at cryogenic temperature. Some factors that may have impacted the cryogenic performances are discussed, which can help to choose better suited components for cryogenic applications. Thus, this work identifies some of the well-performing electrical isolation components for signal circuits that can be placed close to the cryogenically cooled power semiconductor devices for compact and highly integrated converter design.

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