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An IGBT Gate Driver for Operation in High Pressure Hydrostatic Environment

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Abstract

This paper presents results from an on-going research project [1] on pressure tolerant power electronics at SINTEF Energy Research, Norway. The driving force for this research is to enable power electronic components to operate in pressurized dielectric environment, by demonstrating reliable operation [2][3]. The intended application is converters for operation down to 3000 meters ocean depth, primarily for oil and gas processing.
The paper focuses on needed modifications to a general purpose IGBT gate driver in order to obtain pressure tolerance. Adaptations and modifications of the individual driver components are presented. The results from preliminary testing are promising showing that the considered adaptations give feasible solutions.

1. Acknowledgements

This paper presents results from a research project [1] at SINTEF Energy Research, financed by the Norwegian Research Council (PETROMAKS Programme) and industry partners (EXPRO, Petrobras, StatoilHydro, Total, Siemens, Aker Solutions, Shell, and Wärtsilä), and with NTNU as university partner. Several component manufacturers (IXYS, Tyco, Westcode and ICW) are appreciated for very good service supplying test samples and expertise.

2. Introduction

Several oil companies have plans for subsea processing of oil and gas that require power electronic converters as part of the subsea system. Typical applications consider a wide power range, from 0.1-100 kW for electronics and actuators up to several tens of MW for converters for variable speed drives for gas and oil pumping. Today's high power converters for subsea applications are based on concepts where power electronic circuits are assembled in one bar vessels. An example of such subsea installation is the planned subsea compressor station for the Ormen Lange Field in the North Sea which has design depth of 1100 meters. As the sea depth and the converter power rating increases, the pressure vessel becomes very large and heavy. Moreover, due to high wall thickness of the vessels, heat conduction from the power electronic components becomes poor. This increases the complexity of the cooling system. Therefore the oil companies are looking for new solutions for reliable subsea power electronics.

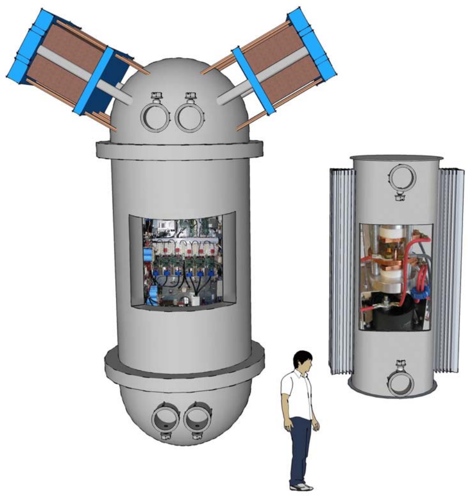

Fig. 1. Representative case of a Today's subsea converter (left) and of a pressure compensated converter (right).

Few scientific papers are found on pressure tolerant power electronics (PTE) [4]-[13], but most of the previous research is outdated due to the new encapsulation and material technologies. Moreover, most of the papers refer to temporary and short time subsea operations such as ROVs.

Therefore SINTEF Energy Research is currently working on a research project that aims to evaluate pressure tolerant solutions for subsea converters, enabling a significant reduction of weight (as illustrated in Fig. 1), cost and system complexity, and increasing the overall reliability of the system. In this work the focus has been to obtain reliable components for long-term subsea operation (10-20 years). The fundamental concept is assuming that the complete power circuit and IGBT drivers are operating in a pressure compensated vessel where the components are subject to the external environment pressure.

3. Methodologies and identification of pressure related issues

The present research started with an evaluation of which components in a power electronic converter are assumed to be the most critical regarding exposure to high pressure. A close collaboration with component manufacturers has been essential to determine the possibilities of custom components design or modification of standard components.

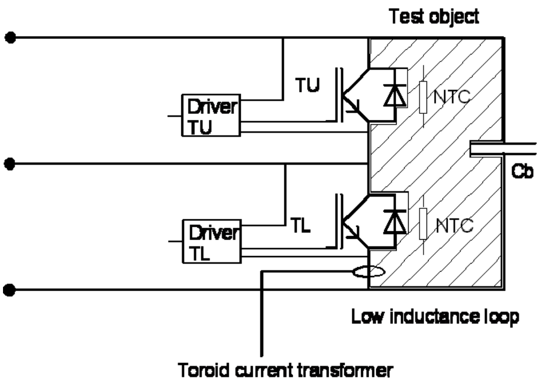

Fig. 2. IGBT phase-leg (test object)

The current work does not aim on developing a complete pressure tolerant converter, but rather to demonstrate feasible solutions by testing modified or custom designed components and on testing and demonstration of live operating circuits in an high pressure hydrostatic environment.

From literature [7] the high pressure failure mechanisms are reported as total permanent mechanical failure, changes in the device characteristics and temporary reversible failure. The most critical components were found to be power semiconductors, power capacitors and driver components. For power semiconductors and capacitors the main concern is related to voids inside the encapsulation. This can be handled by filling the voids with a compatible dielectric liquid. IGBT drivers can be designed for pressure tolerance by selecting components free from voids and which are compatible with the dielectric liquid.

The central control electronics was decided to not be part of this research project since there is quite a lot of results from international work found on pressure tolerant electronics [4]-[7]. Moreover, control electronics has normally a manageable size and weight compared to power electronics so it can be assembled in a small one bar vessel.

A three-phase voltage source converter is considered as representative case. The test circuits are converter phase-legs, composed of IGBT/FWD, dc-link capacitors and gate drivers as illustrated on Fig. 2.

3.1. Liquid insulation

At sea depths of several thousands meters, the power electronic circuits should be filled with an incompressible insulating material that protects the components against mechanical failures. It should act as heat-spreading and should be applicable in such a way that voids are avoided. For these reasons liquids are the first candidate.

Different liquid candidates have been evaluated, e.g. mineral oils, synthetic oils, silicon oils and organic esters. MIDEL®7131 is a synthetic ester that has been selected as main candidate due to its high breakdown strength, low thermal expansion, good tolerance to high moisture levels, good high-temperature stability and relatively low-cost. Further more it is biodegradable and non-toxic.

3.2. Selection and modification of individual components for pressure tolerance

Initially the most critical components of a power electronic converter were identified. The main philosophy for the modifications has been to do as few adaptations to standard components as possible in order maintain their main characteristics. The key factor is to allow the dielectric liquid to penetrate all voids within the components completely. Various forms of protective coatings have also been subject of investigation, especially for components like semiconductor chips and some driver electronics.

Power semiconductors (IGBTs)

IGBTs were classified in two categories: bonded and press-pack IGBTs. A proper insulating media with a pressure compensated housing design would achieve this goal and would avoid any mechanical failure. For the work on pressure tolerant IGBTs [3] is referred to.

Power capacitors

Film capacitors were selected as pressure tolerant candidates, since they are good candidates for both DC-link capacitors and AC-filters. No or only light modification of the active part was required. For the work on pressure tolerant capacitors [3] is referred to.

IGBT gate drivers

An IGBT driver is basically an electronic board composed of integrated circuits and passive components like resistors and capacitors. Therefore most of the challenges regarding pressure tolerance are closely related to challenges considered for pressure tolerant electronics (PTE) in general. Each component has to be evaluated regarding its high pressure adaptability. Vulnerable components have to be replaced by more robust components.

Vacuumization

It is essential to use a vacuum technique for filling all the gaps with the dielectric liquid. This will remove all gas pockets, or they will be reduced to a minimum.

4. IGBT gate driver testing and adaptation

Several IGBT gate drivers are available on the market for general and dedicated applications. However, no certified pressure tolerant driver was found. Most of commercial drivers are realized with resin filled modules. These appear as black boxes that are almost impossible to characterize, both regarding electrical properties and regarding pressure adaptation. For this reason an in-house developed gate driver using discrete components has been chosen.

4.1. In-house gate driver

The in-house gate driver is used as reference driver for modifications. This is a general purpose driver for medium power /medium voltage IGBTs designed at SINTEF Energy Research, Fig. 3. It is designed for driving 1200 V 400 A IGBTs up to 20 kHz.

The main driver characteristics can be summarized as follows:

- Two independent, galvanically isolated gate drivers, with gate voltage of ±14 V and 15 A peak gate current. Independent gate resistors for turn on and turn off.
- Operating range 0% to 100% duty cycle. Turn on delay 3 μs, and turn of delay 1 μs. The turn off delay gives dead time and noise suppression.
- Short circuit protection giving local turn off and fault signal feedback. Blocking time is ~0.2 sec.
- Power supply +15 V (-5% +10%) DC supply, 150 – 500 mA.

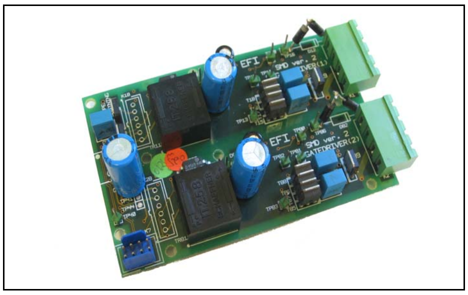

Fig. 3. Original in-house IGBT gate driver

4.2. Modification of the gate driver

Most of the components that are present on the driver are void free and they can withstand a high pressure environment.

Components such as ICs or optocouplers are due to their packaging regarded as uncertain components. However, small devices are less sensitive to external pressure than large packages. Moreover complete epoxy casing can provide void free components that may be well suited for high ambient pressure. Various possible problems need to be sorted out for optocouplers. The optical coupling of these devices may be achieved by a cavity or by a transparent material (e.g. gel). Testing performed on optocouplers with gel did not shown any change in performance after passive pressure test. However they should be subject for more investigations, especially regarding possible long-term degradation.

Electrolytic capacitors are extensively used as buffer capacitors for power supplies on electronic boards, since they provide high capacitance density. However, they tend to have internal voids, and they are not well suited for adaptation to pressure tolerance.

Inductors, transformers and other wounded components contain intrinsic voids due to their design (round cross section wires). External pressure may cause damage to the insulation if these voids are sealed by varnish or potting material, as this could expose the insulation to mechanical stress.

Capacitor replacement

The power supply buffer capacitors (normally electrolytic components) were considered to be the most challenging issue (blue round capacitors on Fig. 3). On each driver board there are three 470 µF 25 V and two 10 µF 25 V electrolytics. Film capacitors may replace electrolytics., however the footprint would increase significantly. Ceramic capacitors are found to be robust against high pressure, but they have low energy/volume ratio compared to their electrolytic counterpart. High-K dielectric materials have increased the energy/volume ratio substantially for multilayer ceramic capacitors. Ceramic capacitors are available up to 10 µF 25 V with smd package 1206 (high-k X5R material). These capacitors assembled in a stack topology, as shown in Fig. 4, can be a good alternative for electrolytics. Moreover, ceramic capacitors are supposed to be superior to the electrolytics, as regards operational lifetime and overall reliability. For obtaining 470 µF, 47 ceramic capacitors connected in parallel would be required. By increasing the switching frequency for the DC-DC supply converter, improved filtering performances or reduced capacitance values could be achieved. For the latter case a filtering capacitor of 120 µF is considered as suitable value and 12 ceramic capacitors have a volume similar to the original electrolytics. Several capacitors of moderate size were preferred instead of large surface ones due to the thermal expansion issues.

Tuning of driver power supply

For the driver power supply electric insulation is provided by a high frequency transformer. The power supply is an unregulated 1:1 forward converter controlled by an IC (UC3845) set for operating at a switching frequency f_{sw} of 60 kHz. Increasing the switching frequency would allow a transformer design with less turns and more space for insulation. Moreover the size of the filtering components can be reduced as well as the output ripple. Based on these considerations the switching frequency was increased to 160 kHz.

High frequency transformer replacement

The original transformer on the in-house driver is a commercial product. It is a high frequency transformer encapsulated in a plastic housing with a soft material. A provocative pressure test was performed. The test-objects were kept pressurized in nitrogen for 48 hours, allowing gas molecule to diffuse into the materials building up pressure in the internal voids. Then the pressure is released abruptly. Any damage caused by the trapped gas reveals the presence of internal voids, as seen in Fig. 5. Due to these observations the transformers were replaced with open housing transformers that allow liquid to penetrate the interior.

For maintaining the same layout factor as the original transformer an EFD15/8/5 core with 3F3 material was chosen. This core, including coil former allows almost a direct replacement of the original transformer, with only a minor correction of the pin layout.

Triple insulated wires represent a good candidate for improving the transformer insulation without additional insulation on the coil former. A twisted pair of triple insulated wires can withstand a nominal operating voltage of 2 kV_{RMS}.

The new transformer has 20 turns per winding of triple insulated wires with a core diameter of 0.2 mm for operating at 160 kHz. Primary and secondary winding are wound separately with the primary winding close to the core and the secondary winding on the outside part. A Melinex® polyester film layer is used for improving creepage and clearance distances of the coil former.

All the modifications have been implemented to the self-made driver (Fig. 6). As a last step the driver performances have been compared and a passive pressure test (no power applied) has been carried out to verify its proper operation.

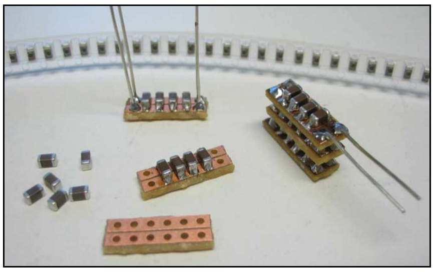

Fig. 4. Stacked ceramic capacitors for electrolytic replacement

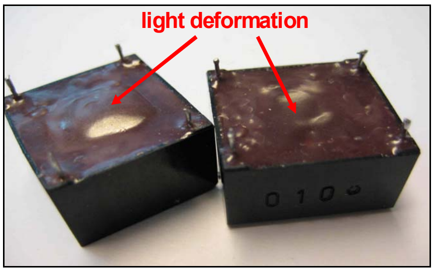

Fig. 5. Examples of damages due to exposure to high pressure hydrostatic environment followed by abrupt depressurization

4.3. Open issues

The modified driver was tested successfully in pressurized environment (see section 5). As there was no pressure vessel with signal penetrators available, this test was performed as a passive pressure test with no power applied to the test object. Some components such as optocouplers and ICs are still an uncertain factor for operating in high pressure environment, although no failures have been observed. However their reliability has to be verified with long term testing exposed to hydrostatic pressure.

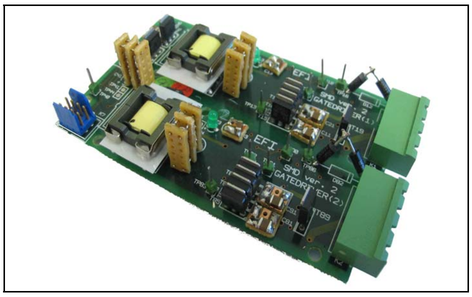

Fig. 6. Modified IGBT gate driver

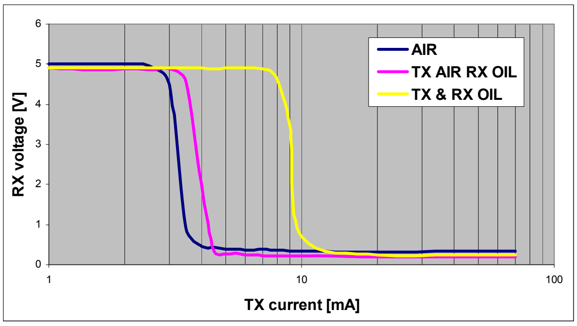

Fig. 7. HFBR-0501 threshold comparison in air and dielectric liquid, logarithmic scale

4.4. High voltage gate driver investigations

High voltage converters require IGBT gate drivers equipped with properly insulated control signals and power supply. The most common solution is to control the drivers with optical fibers. However in dielectric environment the fluid may interfere with the optical coupling. For investigating possible reduction of optical performance two types of optical fibers have been tested: a low cost plastic fiber (HFBR-0501) and a high performance fiber (HFBR-0400). Both optical fiber series were able to operate in dielectric media. However the HFBR-0501 showed a light degradation of performance as shown in Fig. 7 where the threshold current increases. This is probably due to the altered conditions at the lens system at the fiber transmitter and receiver. After a high pressure test the HFBR-0400 series was subject to an internal structural damage that prevented a proper operation of the optical link. The HFBR-0501 type was operating properly even after exposure to high pressure. This can be explained by the simple internal structure where receiver and transmitter are encapsulated with a void free transparent resin that performs the optical coupling.

5. Measurements comparison

The modifications to the gate driver were not implemented all at the same time, but done step by step. Moreover different solutions were investigated, especially regarding the transformer design. The protection functions described in sec 4.1 has not been subject to any modifications, only the gate pulse signal path, and the power supply. Therefore the performance tests were aimed on characterizing the driver output stage in different load conditions.

The tests were performed with dummy load capacitances of different values (from 10 nF up to 470 nF) instead of IGBTs. Switching frequencies were in the 5-20 kHz range according to Table 1. The first test aimed to characterize the no-load condition of the driver. During the test the load (f_{sw}*C product) was increased gradually. Output voltage and input current were measured.

The modified prototype pressure tolerant driver is compared with the original driver, at various loads, as shown in Fig. 8. The modified driver has better performances, in the sense that the voltage drop is less in all test conditions. However its current consumption increases slightly (about 30 mA). The main cause of this difference is the redesigned converter stage.

The measurements performed after a passive pressure test Fig. 9 have demonstrated that the driver is able to withstand a high pressure environment without degradation of performances. Pressure test was performed with both low and high slew rates dP/dt (pressure increase /decrease as function of time).

TEST CONDITION:	Switching frequency for IGBTs [kHz]	Load Capacitance [µF]
1	0	0
2	20	0.01
3	10	0.1
4	20	0.1
5	5	0.47

Table 1. Specification of test conditions

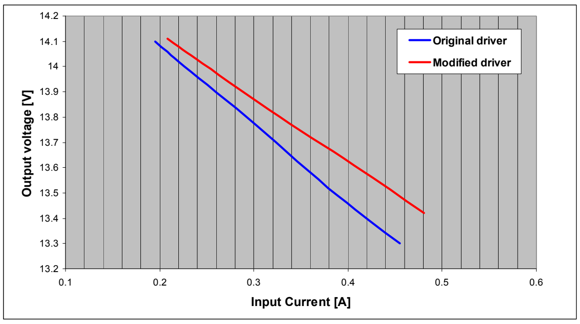

Fig. 8. Original (blue) and modified (red) drivers, output voltage as function of current drawn at input

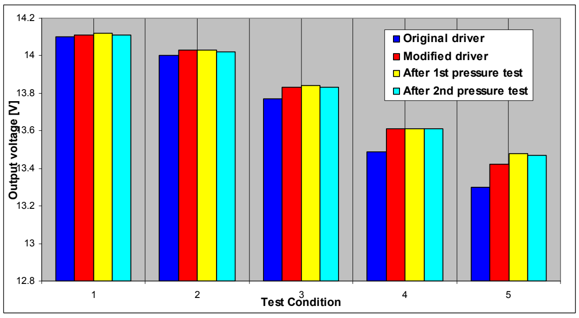

Fig. 9. Modified driver, before pressurization (blue), after first pressurization (red) and after second pressurization (green)

6. Conclusions

Benefits by using pressure compensated solutions for subsea power electronics are the main driving force for this project. Initial tests and component analysis identified critical components for high pressure environment. Feasible techniques and adaptations for obtaining a general purpose pressure tolerant IGTB gate driver has been analyzed in this paper. It has been demonstrated that with simple and focused modifications, it is possible to obtain a pressure tolerant driver with performance similar to the original design. Pressure tolerant optical connection can be achieved with some loss of performance of the optical link, provided that suitable components are used.

Passive pressure testing of components revealed that some components had internal voids that made them unsuited for pressurization.

This project will continue with a full pressurized phase-leg (IGBTs, power capacitor and IGBT driver as illustrated in Fig. 2) operating in dielectric liquid with applied power (February 2010). Test object will be exposed to MIDEL® 7131 at 300 bar for long term operation to verify the overall system reliability.

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