Pressure Tolerant Power Electronics: 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. The main goal for the research is to provide and demonstrate solutions that enable power electronic converters to operate in pressurized environment. Oil companies have plans for subsea processing of oil and gas. Today’s concept considers power electronic converters in one bar vessels. As the depth and the converter power rating increase, these vessels become increasingly bulky and heavy. Pressure balanced converters would allow lower vessel wall thickness, thereby giving lower weight, and simpler cooling due to improved heat conduction through the vessel walls. The new concept considers the power electronic converters placed in vessels completely filled with appropriate dielectric liquid able to operate at pressures from 1 bar up to several hundred bars. Dielectric fluids are required to prove their properties especially related to insulation, incompressibility and heat transportation. The methodology presented here considers a mechanical adaptation of components followed by various laboratory experiments for verifying or correcting the proposed solutions [2-4].

Standard off-the-shelf components and special pressure adapted components have been subject to various provocative pressurisation tests up to 300 bar. Tests clarified the need for special adaptation of some components, while others could be used without any modification. Subsequently a full converter phase-leg has been built, submerged in dielectric liquid and tested in full operation up to 300 bar. This phase-leg is based on a press-pack IGBT modified for operation at high pressure. Measurements performed at different pressures demonstrate that there is no relevant difference in terms of electric parameters between this modified IGBT and a standard IGBT. Long-term tests proved the concepts goodness. The next step will test bonded IGBT technology in high-pressure environment, and finally will realise a test demo to be located at a suitable subsea site.

Introduction

Several new oil and gas wells worldwide are located offshore where the sea depth can reach 3000 m. Offshore platforms for oil and gas processing are expensive and often exposed to extreme conditions, for example in the North Sea outside the coast of Norway. For reducing the processing costs and for increasing the recovery factor, many companies have plans for subsea processing of oil and gas that require power electronic converters for various applications. The converter power range is from 0.1-100 kW (valve actuators, UPS etc.) up to tens of MW for variable speed drives for oil pumps and gas boosting. The today’s installations are based on concepts where power electronic converters are assembled in one bar vessels. One example of such installation is the Ormen Lange Field in the North Sea which has a design depth of 1100 m and a converters rating of 12.5 MW [5]. As the converter power rating and the design depth increase the vessels become increasingly bulky and heavy due to the high wall thickness required for coping with the pressure difference. Pressure balanced vessels will give significantly reduction of weight. Moreover, the cooling system for removing converter heat-losses may become more reliable and less complex since the heat can be more easily conducted through the thinner vessel walls, instead of by separate heat exchangers Fig. 1. Therefore the oil and gas industry has shown an increasing interest for pressure balanced solutions.
Only few scientific publications have been found on pressure tolerant power electronics and most of them are outdated due to the new encapsulation and material technologies [6-14]. Moreover, most applications refer to short time or temporary subsea operation. The present research started with an evaluation of the most critical components for pressurization of a power electronic converter. These were found to be IGBTs, gate drivers and dc-link capacitors. A close cooperation with component manufacturers has been essential for the investigation of possibilities for modification of standard components or for design of new components suitable for pressurization. In the present research the control electronics part of the converter has not been focused. One reason is that open results from international research on pressure tolerant electronics is more accessible than for power electronics. Another reason is that converter control electronics can be easily separated in pressure compensated and relative small stand-alone units with a tidy interface (fibres etc.) to the power circuit. The exception is the gate drivers. They need to be placed close to the IGBTs and therefore they are also part of the pressurized converter power circuit.

The power circuits of single-phase (H-bridge) and three-phase Pulse-Width Modulated (PWM) converters are composed of two, respectively three identical phase-legs with a common dc-link capacitor bank [15]. Therefore the converter selected as test object for most of the live experiments in the present research consist of a phase-leg with free-wheeling diode, IGBT and gate driver, and one or more dc-link capacitors. Such a test circuit will represent single-phase as well as three-phase and multi-phase PWM converters.

Fig. 1 Today’s subsea converter (left) and pressure balanced converter (right)
Selected and tested components

Allowing power electronic converters to operate at sea depths of thousands of meters require that power electronic circuits are enclosed in a vessel filled with an incompressible media with the appropriate insulating characteristics, a liquid dielectric media. It is essential that the chosen dielectric liquid is applicable in such way that voids are avoided. In addition to being a good insulator, the dielectric liquid should also provide good heat-spreading qualities (to enhance the system cooling) and it should be relative cost-effective since large volumes will be required. Already established, and well-proven liquids used for other electric components are preferred. Several liquid candidates have been evaluated such as mineral oils, synthetic oils, silicon oils and organic esters. The selected liquid for the present test circuit is Midel®7131, a synthetic ester. Midel®7131 has been selected due to its high breakdown voltage, good tolerance to high moisture levels, low-cost, good high temperature stability and its non-toxicity and biodegradability [16-17].

The initial analysis highlighted the most critical problems, which were found to be mostly related to housing and material compatibility. Special housing designs have been subject to investigations. The housing should allow complete liquid filling of any voids inside the components. In addition, special coating materials have been considered as possible additional sealing and protection layer, and as possible interface material between the component surface and the surrounding liquid. This is important especially for IGBT chips and bondings where electric field strength is very high.

Several component candidates with quite different constructions and housings have been subject to investigation and testing. The selected candidates represent the actual state of the art of power components for power electronic converters. Two IGBT technologies were considered: bonded IGBTs and press-pack IGBTs. Standard off-the-shelf components and custom designed components were analysed and tested. The present paper, however, is discussing only the press-pack alternative since this was found to be most challenging regarding adaptation for pressure tolerance, and since the press-pack design has so far been subject to most live testing at high pressure. From the different candidates for dc-link power capacitor, film capacitors were chosen as main test object due to good data on energy density and lifetime. Off-the-shelf and custom designed capacitors from three manufacturers have been analysed and tested. Two IGBT gatedrivers were investigated for pressurization: a commercial high voltage gatedriver and an in-house developed driver.

Fig. 2 Structure of an off-the-shelf press-pack IGBT (left, source Westcode) and concept for adaptation to pressure tolerance (right).

Fig. 3 Component failures after exposure to high hydrostatic pressure; left: capacitor on IGBT gate driver; center: off-the-shelf unmodified IGBT module; right: modified IGBT module (holes) for pressure tolerance.
Initial pressurization of standard and modified components

After the initial analysis, the test programme was started by exposing the individual converter components to various provocative pressure tests without applied voltage (passive tests). These tests also included pressure cycling with extremely high slew rates. A kind of “worst case” test with gas (nitrogen) up to 100 bar was also performed. Gas penetrates easier inside the components compared to most liquids and gas tests are thus expected to enhance failures and components deformations. Moreover, the high slew rates applied (up to 100 bar in 12 sec) also produced large mechanical stresses to the components compared to more realistic low slew rates. A second type of passive pressure test was performed with Midel®7131 up to 300 bar. This test confirmed that some off-the-shelf components are unsuitable for pressurized applications and their failure leads to a permanent damage of the component or of the housing as illustrated in Fig. 3. The same test also proved that modified housings or special designed or modified components can relieve the pressure stress and they can withstand high hydrostatic pressure even with high slew rates during pressurization.

Description of the pressure adapted test converter

Phase-legs feasible for pressurization were designed for testing two quite different IGBT designs. One was the press-pack encapsulation (Fig. 2) and the other was the bonded planar module (Fig. 3). Standard press-pack IGBTs are built by paralleling of several IGBT and free-wheeling diode (FWD) chips. A standard press-pack IGBT has a sealed housing filled with SF₆ gas. Its structure and a way to pressure adapt it is shown in Fig. 2. In a pressurized application, the gas has to be replaced by the chosen incompressible liquid. For this project, a test converter was designed applying one IGBT chip and one diode chip forming a phase-leg chip assembly as shown in Fig. 7. The separate chips, without the press-pack housing, were delivered by the manufacturer. The component used as reference is the standard Westcode press-pack IGBT T0360NA25A (2.5 kV 360 A), containing five IGBT chips and two FWD chips of the same types as our phase-leg assembly. Rating for each IGBT chip is 2.5 kV and 72 A, while each diode chip is rated 2.5 kV and 180 A. The phase-leg assembly was carefully designed in order to maintain the same contact force on each chip as in the original press-pack housing.

The test processes for the pressure adapted converter

Two types of tests were performed on the phase-leg test object: one was what we have called a double-pulse test. The other was a continuous switching test. Double-pulse testing is used to characterize the converter phase-leg up to its maximum switching voltage and current (72 A), without giving significant temperature rise for the chips. Two short pulses (range 7~150 µs) are applied followed by a 1 sec off period with no current flowing, as illustrated in Fig. 5. Continuous switching tests were performed applying reduced current due to the limited cooling capabilities of the designed phase-leg. Both tests use the same circuit topology Fig. 4.

A pre-test of the phase-leg was performed in air environment with a limited DC-link voltage applied. Then the phase-leg was tested in Midel®7131 in a 1 bar environment with increasing DC-link voltage. To ensure that no gas particles or voids were present in the liquid, the dielectric fluid was degassed and the test object was filled using vacuum technique. The initial tests with reduced dc-link voltage and current verified that there was no difference in the in the switching waveforms between the phase-leg operating in air or in the selected dielectric media, see Fig. 6. Operation at 1 bar is expected to be the most critical in terms of voltage breakdown since the breakdown strength of the liquid is improving with increasing pressure [17]. During the one bar test, the test object was located in a glass container completely filled with the selected dielectric liquid.

For the following high-pressure tests, the phase-leg was positioned inside the pressure vessel by fixing it to the lid of the vessel, as shown in Fig. 7 and 9. In order to minimize the risk for air pockets the whole vessel was vacuumized before it was filled with degassed Midel®7131. Finally, the pressure vessel was connected via a membrane to an accumulator pressurized with nitrogen. The membrane guarantees a separation between the two media (nitrogen and dielectric liquid) and, at the same time, it provides margins regarding thermal expansion. This was necessary since when the phase-leg was operated continuously it generates heat that causes the dielectric liquid to expand. The pressurization slew rates were kept considerably lower than in the passive pressure tests described previously. The pressure increase was performed in steps, and electrical measurements were performed at each step. Before continuing to the next step, the electrical operation was paused for 24 hours to allow pressure stabilization. At the last step, the operating pressure of the phase-leg reached 300 bar. From that point, the test object has been continuously running as a long-term reliability test. The long-term test will run until February 2011. Then it will be stopped, and the test object will be taken out of the pressure chamber and be subject to various post-examinations.
Fig. 4 Test circuit diagram including the test object with Devices Under Test (FWD and IGBT).

Fig. 5 Double pulse testing waveforms.

Fig. 6 Measurements of switching waveforms in air and in dielectric liquid (Midel®7131) at 1 bar.
Fig. 7 Mechanical structure of the IGBT and FWD chips assembled as a phase-leg (left) and the complete phase-leg assembled on the pressure vessel lid.

Fig. 8 Switching waveforms for the chip assembly phase-leg up to 1.5 kV DC-link 1 bar.
Fig. 9 High pressure vessel used for testing pressure tolerant power electronic converters.

**Presentation of Test Results**

The DC-link voltage for the pressure vessel test had to be limited due to voltage limitation of the electric penetrators (maximum 1 kV). Considering the switching overvoltage at turn-off, the maximum dc-link voltage was set to 600 V. Diode and IGBT current and voltages waveforms were recorded for switching tests done up to 300 bar hydrostatic pressure. Two groups of waveforms are presented; one group comparing cases up to 50 bar and the other group comparing cases up to 300 bar. Grouping of measurements was necessary to avoid overlapping of too many waveforms. Moreover, possible mechanical failures are mainly expected up to 100 bar (that corresponds to ~100 kgf per cm²) since already at this pressure the components are subject to large mechanical stresses. Measured data were stored and post-processed allowing the scope triggering points to be aligned for the presentation.

**Table 1 Testing pressures for IGBT phase-leg**

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IGBT turn-on and at turn-off voltage waveforms are presented in Fig. 10. Waveforms from 1 bar up to 50 bar are compared. It is clear that the IGBT switching waveforms are not affected by the external pressure. In fact, all waveforms from 1 bar to 50 bar overlap each other with almost no difference at all. A small difference can be observed for the transistor turn-off waveform at 10 bar as the transistor turn-off tail is slightly moved leftwards. The only observable difference has been identified as a small difference in the scope triggering alignment. Transistor voltage at turn-off reaches a peak of approximately 900 V that gives good margin to the 1 kV limit for the penetrator. Similar waveforms for the diode operated at 1 bar to 50 bar are shown on Fig. 11. As observed for the IGBT waveforms, both diode turn-off (IGBT turn-on) and diode turn-on (IGBT turn-off) do not show relevant differences for the various operating pressures. All in all the waveforms for both the IGBT and the diode have good overlapping. This is an indication that the electrical characteristics of the power semiconductors are not influenced by the applied operating pressure.
The complete pressure range between 1 bar and 300 bar is analysed in the same way as described above for the 1 bar to 50 bar range. IGBT and FWD voltage waveforms at turn-on and turn-off for different pressures are analysed Fig. 12 and 13. The analysed waveforms for both devices (FWD and IGBT chip assemblies) do not highlight differences that could indicate possible critical issues or failures. This indicates that the test converter is not affected by the external hydrostatic pressure when it is operating in the selected dielectric liquid. This includes selected and adapted power IGBT and FWD, dc-link capacitors and IGBT gate driver components including selected optical fibers.

The results demonstrate that the selected concept for enabling pressure tolerant operation of critical power electronic components is feasible. High hydrostatic pressure has proven not to affect the electrical behaviour of the specially designed chip assembly phase-leg converter. This long-term test continues until February 2011, operating the converter at 600 V, 10 A and with hydrostatic pressure of 300 bar. The current is low due the limited cooling capacity of this test setup.

![Westcode Press-Pack IGBT Turn on comparison 1 - 50 bar](image)

Fig. 10 IGBT turn-on and turn-off voltage waveforms at different pressures between 1 and 50 bar.

![Westcode Press-Pack IGBT Turn off comparison 1 - 50 bar](image)

Fig. 11 FWD diode voltage waveforms at different pressures between 1 and 50 bar at IGBT turn-on/off.

![Westcode Press-Pack IGBT Turn on comparison 1 - 300 bar](image)

Fig. 12 IGBT turn-on and turn-off voltage waveforms at different pressures between 1 and 300 bar.
Bonded modules without gel were tested at 1 one bar for about a one year and half period with good results. This is very uplifting. It shows that gel can be replaced by proper dielectric liquids without deteriorating the module performances. Voltage breakdown strength for insulating liquids is assumed to improve by increasing pressure [17]. The chips will be directly exposed to any contaminations in the liquid. This can cause long-term issues such as flashovers.

In 2011, similar tests will be carried out for planar, bonded IGBT modules with gel as well.

Conclusions
Pressure tolerant power electric converters have the potential for enabling more reliable and less complex subsea installations for oil and gas processing. Initial studies of component operating characteristics and encapsulations have indicated that complete pressurization of the converter power circuit is feasible by modification of the encapsulation of the most critical components. Provocative pressure test of individual components with no voltage applied has confirmed the critical encapsulations issues.

A special pressure adapted phase-leg converter assembly based on press-pack IGBT and diode chips has been built and successfully tested up to 300 bar. No deviations have been observed in the electric characteristics in the 1-300 bar operating range. The tested converter included IGBT and diode chip assemblies, a power capacitor and commercial gate driver with its optical fibers. All components successfully passed the test and no relevant failure has been recorded. By January 2011, the converter had been tested at 300 bar for a period of three months. The observation that the electrical characteristics of the silicon chips do not seem to be influenced by the applied pressures is perhaps the most important outcome from the presented work. The main challenges for succeeding with pressure tolerant power electronics is related to packaging methodologies, and especially to finding the most suitable materials and insulating material combinations.

Although the presented results in this paper are very promising, there are quite a few questions left to be answered. One such uncertainty is related to requirements regarding liquid purity in the close vicinity of the IGBT and diode chips where the electric field strength is very high. New ideas have emerged during the test programme on how to improve encapsulations for liquid isolated components, especially preventing contaminants to access the chip. Continuing activities are proposed.

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