Enabling pressure tolerant power electronic converters for subsea applications

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Abstract
This paper presents results from an on-going research project on pressure tolerant power electronics where the power electronic components are enabled to operate in a pressurized dielectric environment. The driving force for the research is to provide new solutions for subsea high power converters that can get benefits by reduced weight and volume of pressure chambers, reduced number of electric power penetrators, obtain less complexity and more reliable cooling system, reduced costs and increased overall reliability.

The components of most concern have been power semiconductors, power capacitors and IGBT gate drivers. Even though the work reported in this paper is still in progress, the basic investigations and experimental work so far indicates that reliable solutions for pressure tolerant power electronics has a high potential for success, when all power components and gate driver electronics are vacuumized and soaked in a proper dielectric fluid. This is valid for the individual components as well as for the complete circuits. Also the feedbacks from the components manufacturers are uplifting in that respect.

Introduction
Several oil companies have plans for subsea processing of oil and gas that need power electronic converters as part of the subsea electric installation. Typical applications are motor converters for gas boosting and oil pumping. The today's converter designs offered by the industry aimed for subsea operation are based on concepts where the power circuits are completely assembled in one bar vessels. As the sea depth and the converter power rating increase, the pressure vessels gradually becomes heavy and unwieldy modules. Due to high wall thickness of the vessels, the heat conduction from the power electronics components to seawater also becomes problematic. Therefore the oil companies are looking for more feasible solutions for subsea power electronics. Enabling pressure tolerant power electronic circuits is a significant step in that direction.
Identification of problems and priority settings for the research

While quite a few scientific papers are found on pressure tolerant electronics, [9]-[15], results from open research on pressure tolerant power electronics seems to be poor. Much of the previous research is also outdated as result of new encapsulation and material technologies. Own work from the eighties, [8] involved investigations of pressure adaptability for metal and plastic encapsulated transistors, polypropylene capacitors, and various electronic components. Methods for pressure balancing electrolytic capacitors by using accumulator filled with electrolytic liquid for interfacing external liquid, was also investigated. Furthermore most of the papers are referring to applications aimed at short time or temporary subsea operations (e.g. ROVs), [5]-[6]. Therefore the present research was started from scratch with an evaluation of components in a power electronic converter that was assumed to be most critical regarding exposure to high environmental pressure. In parallel, discussions with representative component manufacturers were started regarding possibilities for special designs for the most critical components found, or modification of standard components.

The main conclusions from the initial evaluations were as follows:

- The most critical components were found to be power semiconductors, power capacitors for filtering and dc-link, and some driver components
- For the power semiconductors the encapsulations will be the most critical problem. Modification for pressure tolerance is possible by modifying existing housing, e.g. filling voids with dielectric liquid and by pressure balancing
- Some film capacitor candidates have potential for pressure adaptation by small modification of filling material
- IGBT drivers have also the possibility for pressure adaptation through special circuit designs and by selecting components free from voids
- Some components may need special coating for sealing. Especially IGBT chips and bondings, when gel is replaced with a dielectric liquid. Various coating methods and materials have been evaluated.

Fig. 1: One bar pressure chamber versus pressure compensated chamber, assuming container for a 15 MW subsea converter at 3000 m sea water

- Container for 1 bar internal pressure: 60000kg (wall thickness 100mm)
  - Thick steel walls ➔ Need for complex cooling system
- Pressure compensated container 6000kg (wall thickness 10mm)
  - Thin steel walls ➔ Possibility for conductive heat transfer through walls
For the following reasons, central converter control electronics was decided to not be a part of the research project:

- Pressure tolerant electronics has previously been subject to research, and quite a few publications are found on the subject.
- Except for the drivers for the switching devices, control electronics has normally a tidy physical and electrical separation from the power circuit. Therefore a converter control pod can easily be arranged as separate unit.
- Regardless the converter power range, control pods will be small units that can be assembled in a one bar vessels with manageable size and weight.

The present research does not aim to develop complete pressure tolerant converters for specific applications, but rather to demonstrate feasible reliable solutions by testing modified components for pressure tolerance, and by pressure testing of live power circuits constituting these components. The test circuits are converter phase-legs, composed of dc-link capacitors, IGBT/FWD and gate drivers, as illustrated in fig 2. Voltage and current range for the test objects are 1.2-4.5 kV and 100-400 A (switching current) respectively. The test object can be regarded as building-blocks for complete converters, also including high power converters.

**Selection and modification of individual components**

As argued ahead the most crucial components of a pressure tolerant switching converter power circuit was found to be the switching IGBTs, the power capacitors (for dc-link, output filter) and the IGBT driver circuits. The main philosophy for the modifications of components has been to do as small modification of the standard components as possible, by allowing a dielectric liquid with the proper qualities to fully penetrate all voids within the components. Prioritized qualities for the dielectric liquids are low relative compressibility, high dielectric breakdown voltage, low viscosity, high electrical resistibility and chemical compatibility with the component materials. Prioritized liquid candidates for the initial research have been Midel® 7131 transformer fluid and Silicone oil Dow Corning 200(R) Fluid, 50 cSt l.
Various forms for protective coatings have also been subject for discussions, in particular for components like semiconductor chips and some driver electronics components like IC’s.

Discussions regarding selection of fluids and candidates for coating materials are presented in [3].

The modification of components has also been part of special experiments by doing provocative pressure testing of passive components, as will be explained later.

Currently the following components have been subject for various experiments, both as individual components, and as part of switching phase-leg modules:

- **Four IGBT/FWD components from three sources**
  - Sample I: Bonded 300 A, 1200 V module (Source I) - custom made and off-the-shelf
  - Sample II: Bonded 300 A, 1200 V module (Source II) - custom made and off-the-shelf
  - Sample III: 72 A, 2.5 kV Press-pack/ hockey-puck IGBT/FWD component (Source III)
    - a) Single chip IGBT and FWD
    - b) Complete press-pack device - custom made and off-the-shelf
  - Sample IV: 53 A, 4.5 kV Press-pack/ hockey-puck IGBT/FWD component (Source III)
    - a) Single chip IGBT and FWD
    - b) Complete press-pack device - custom made and off-the-shelf

- **Three power capacitors from three sources**
  - Sample I: 900 V, 460 µF metallised Polypropylene Film Capacitor - Standard Component
  - Sample II: 1100 V, 100 µF metallised Polypropylene Film Capacitor - Slightly modified
  - Sample III: 800 V, 600 µF Film Capacitor - Modified for liquid and pressure tolerance

- **Two IGBT drivers from two sources**
  - A pressure adapted driver based on a proven standard in-house developed driver aimed for low-voltage (1200 V) IGBTs
  - A standard commercial driver aimed for high voltage (4.5 kV) IGBTs

This assortment of components is partly reflecting the need for having a representative selection of the critical components, partly based on the willingness from manufacturer regarding delivery of custom fabricated components and cooperation regarding pressure adaptation. The reason for not selecting any electrolytic capacitors as candidates for pressure adaptation is firstly that they represent a poorer basis for pressure adaptation, also as assessed by the manufacturer, secondly that modern film capacitors are about to replace electrolytic capacitors as dc-link capacitors.

**Bonded IGBTs**

Bonded IGBT modules from two manufacturers were selected. This includes both standard off-the-shelf components and custom fabricated components. The off-the-shelf components were intended for reference measurements in normal one bar environment. The custom fabricated components are more or less adapted for running in liquid and pressurized conditions. The modules are custom components in the sense that they have been taken out from the production line before filling with silicon gel. Adaptations for pressure testing are discussed in detail in [3].

**Press-pack IGBTs**

The press-pack custom components are delivered as open unwelded structures without the standard gas filling.

The IGBT press-pack technology has been subject to a multiple of special experiments in order to clarify the effect of replacing gaseous dielectric environment with dielectric liquid. A press-pack device is composed of several IGBT chip assemblies and FWD diode chip assemblies in parallel. Most of these experiments are on such single assemblies, rather than on complete press-pack devices.
The following tests have been accomplished or are in progress on single chip assemblies:

- Electric properties of press contacting in dielectric liquid Midel® 7131
- Investigation of vacuum filling feasibilities on chip assemblies and complete press-pack device
- Dielectric tests of diode chip assembly in liquid up to rated blocking voltage (2500 V)
- Dielectric tests up to 10 kV of chip assembly with chips replaced with a passive insulation material

Accomplished tests in liquid at one bar indicate that there is a good chance to obtain pressure tolerance for press-pack devices by vacuum filling with dielectric liquid. These tests will now continue at increasing environmental pressure up to 300 bar. Adaptation for pressure testing of press-pack devices are discussed in detail in [3].

**Power Capacitors and status regarding pressure adaptation**

Power capacitors, suitable as dc-link capacitors, have been provided from three manufacturers. One is not modified at all, while the two other are more or less modified for pressure tolerance. The process for obtaining pressure tolerance has been supported by provocative pressure testing of components (see following section) followed by dedicated long-term electric testing of components at one bar liquid environment, and follow up from manufacturers regarding adaptation of components. The test setup for long-term testing of capacitors is an arrangement where the test-object is subject to both controllable dc-voltage up to maximum rating, and controllable ripple current up to maximum levels (limited by temperature).

Status for the individual capacitor test samples are as follows:

**Sample I:**
- Long-term testing of capacitors submerged in silicon oil has been running for about six months without experiencing operational problems
- One of the specimens have also been subject to a special pressure test in 100 bar nitrogen atmosphere, without any observed damage (see subsequent section)
- One specimen has been subject to a 300 bar passive test in Midel® 7131

**Sample II:**
- Some samples are subject to live testing in liquid and pressure as part of the test programme for power circuits in switch-mode operation.
- One of the specimens has also been subject to a special provocative pressure test in 100 bar nitrogen atmosphere. This test unveiled a mechanical weakness that has been corrected by the manufacturer.
- One specimen has been subject to a 300 bar passive test in Midel® 7131

**Sample III:**
- Some samples of a special component adapted by the manufacturer for liquid and pressure tolerance has been provided for the test programme, but presently no tests have been initiated.

**IGBT drivers**

A pressure tolerant gate driver for low voltage applications (<1000 V) has been developed by modifying an existing driver developed at our institute. The critical components have been replaced in the sense that electrolytic capacitors are replaced with stacked ceramic capacitors and the power supply transformer has been redesigned for pressure tolerance. The result is a driver with similar performances as the original. The pressure tolerant in-house driver and the comparison of the performances are shown on fig 3.

Several driver candidates have been prepared for various tests in air and in dielectric liquid Midel® 7131. The drivers have been exposed to an initial provocative passive pressure test at 100 bar in
nitrogen environment. During this test electrical power was not applied. As expected the unmodified in-house driver failed, while the reinforced driver passed the test without any degradation of performances. On the unmodified driver the electrolytic capacitors had the most visible damage. However also the transformers on the unmodified driver showed some light mechanical deformation.

A standard commercial off-the-shelf high voltage driver, without any adaptation for pressure tolerance, has also been tested. This driver has a sealed black module that was expected to be the most fragile component when exposed to high pressure. Surprisingly the standard commercial driver survived the 100 bar provocative test. Detailed information was obtained for this driver and it appeared that the black module is filled with resin by using a vacuum technique. This indicates that vacuum filling of solids can be a feasible candidate for obtaining pressure tolerance for electronics and power electronics. The commercial high voltage driver will not be subject to further work on pressure adaptation, but the research project will evaluate high voltage driver topologies and component candidates suitable for adapting to pressure tolerance.

It is assumed that a high voltage driver needs an optical fiber link for signal transmission across the high voltage barriers. Therefore opto-transmitter and receiver candidates have been investigated in order to clarify whether they can operate in oil and in high pressure. An initial test was aimed to verify the compatibility of two different series of optical fibers with a dielectric liquid. The two tested candidates were the HFBR-0501 and the HFBR-0400 by Avago Technologies. The first candidate is the one used for the commercial driver described above, while the second one has better performances in terms of bandwidth than the first candidate. The HFBR-0501 was able to operate in oil and in high pressure environment with a little reduction of performances. The other series was able to operate in oil but not in pressure environment. In this last case the internal structure of the devices collapsed due to air pockets.

The design of an auxiliary pressure tolerant power supply has been carried out as a part of a master work [16]. The challenge was to design a power supply that was pressure tolerant and that could withstand high bias voltages. The analysis has considered different topologies and various suitable components for this application. The final design, based on a topology that does not require a feedback between the input and the output of the power supply, appeared to have interesting performances.

![Fig. 3: The pressure tolerant in-house driver and performance comparison between original driver and pressure tolerant driver for different load conditions.](image)

**Provocative testing of passive components at 100 bar and at 300 bar**

A representative selection of components like IGBTs, capacitors and IGBT drivers has been subject to a special provocative pressure test in 100 bar nitrogen atmosphere. This is a test where high pressure is maintained for 48 hours, and where the rate of change of compression and decompression is high (12 sec). The aim of the test was to sort out which are the most fragile components in high pressure environment. The test is provocative, since the components are exposed to gaseous environment, and since the slew rate for pressurizations /depressurization is significantly higher than will be the situation in real offshore installation operations.
A second pressure test has been performed on the components that passed the first test. During this test the components were submerged in dielectric liquid (Midel® 7131), and the pressure was increased up to 300 bar. All components were initially vacuumized to ensure that all the air pockets are filled with the dielectric liquid. The compression period lasted for 20 min, the pressure was maintained high for 61 days, and then the pressure was released within a period of 7 min.

**Results from provocative testing in 100 bar nitrogen atmosphere**

One custom fabricated IGBT (Sample I) and an off-shelf IGBT (Sample II) were exposed to the 100 bar nitrogen test. The custom fabricated IGBT had no visible mechanical damage and also passed the electrical functional test following decompression. As expected the housing of the standard off-the-shelf IGBT module cracked during the decompression phase, and soft gel squeezed out from the cracks between the plastic housing and the base plate as shown in fig.4. The power capacitors had some small visible outer marks as result of the rapid decompression (discolour and small cracks in encapsulation). However, also the capacitors passed the electrical function test following the decompression. Different types of small capacitors were tested. As expected electrolytic capacitors are not able to withstand high pressure due to their internal air cavities. Other types such as ceramic and polyester capacitors survived the test even if some of them had some light deformation of the housing. The most relevant damages are shown on fig 4.

**Results from provocative testing in 300 bar dielectric liquid**

The same power capacitors, drivers and a pressure adapted off-the-shelf IGBT (Sample II) were exposed to the 300 bar test in dielectric liquid. All the components passed the electrical tests after the decompression. However even in this case light traces of pressurization were observed. One power capacitor has shown a crack in the housing that has not affected the electrical structure. On the commercial off-the-shelf driver the solid electrolytic capacitors had some light compression marks on the top surface.

The main conclusion from the test is that most of the components need more or less mechanical modifications for adapting to pressure tolerance. Proper modification of housing will ensure pressure tolerance.

![Fracture](image)

Fig. 4: Damages due to exposure to a 100 bar provocative test with nitrogen.

**Test program for power circuits in switch-mode operation**

For each of the two bonded type IGBT modules (Sample I and II) two complete converter phase-leg test modules, which are close to identical, have been constructed. One is intended for a reference module to be operated in normal one bar air environment. The second one is intended for pressure tolerant operation in liquid environment. Each test module is composed of a phase-leg IGBT module, a dc-link capacitor (one of the pressure tolerant samples), IGBT drivers (the modified pressure tolerant in-house driver), sensors for current and temperatures, and heat sink and other mechanical supportive assembly components.

A complete 2.5 kV chip assembly phase-leg module has also been constructed, comprising a lower IGBT chip assembly, and an upper FWD chip assembly, two dc-link capacitors in series (pressure tolerant samples), and IGBT drivers (4.5 kV commercial driver). A similar assembly is also about to
be prepared for switch-mode testing of the 4.5 kV chip assemblies. Also a phase-leg module comprising the custom made complete press-pack modules will be prepared for live operation in liquid pressurized environment. Circuit diagram for the test setup for testing pressure tolerant phase-leg modules is shown in fig 5.

Fig. 5: Test setup for testing pressure tolerant phase-leg modules

**Summary of results from the switch-mode test program**

The above described test modules have been subject to various tests during switch mode operation, when stressed up to applicable dc-link voltage and collector current. Currently the pressure tolerant modules have been running in the dielectric liquid Midel®7131 at one bar, but eventually they will be subject to increasing pressure up to 300 bar. The preliminary results from these tests, also involving comparison between reference module and pressure tolerant module, are that there are no indications that the performances of the components have changed as result of liquid environment. More details regarding the switch-mode test setups and results from the executed tests are reported in [3].

**Dielectric testing of IGBTs**

One important problem to be addressed when the semiconductor chips are directly exposed to dielectric liquids instead of gels or gas is whether the new dielectric materials have other properties regarding voltage withstandability. Of special importance is the effect of presence of contaminations in the liquids. Various tests on live switching circuits and dedicated high-voltage tests on representative test objects have been, and will be conducted in order to quantify any possible problems. E.g. dielectric tests up to 10 kV of chip assembly with chips replaced with passive insulation material have been carried out Midel®7131 without any problems observed. These tests and tests of the switching phase-legs will continue when the test objects are subject to liquids with controlled contaminations. Plans for countermeasures, e.g. by coating have been prepared, in case problems are experienced during the tests.

The most important research work, however, on these subject is about to be carried out as a PhD work, finance by the research project. This work includes material investigations, numerical field calculations and laboratory experiments on well established test cells for such experiments (e.g.
needle-plane gaps), as well as on real 1.2 kV, 2.5 kV and 4.5 kV IGBT/FWD chips. Special tests cells like the one shown for partial discharge measurements in fig. 6 have been prepared for this work. The experiments are to a high extent following the methods of measurements described in [2], [4] and [8].

Fig. 6: Partial Discharge (PD) measurements on semiconductor specimens in liquid

Conclusions and further work

Even though the work reported in this paper is still in progress, the basic investigations and experimental work so far indicates that reliable solutions for pressure tolerant power electronic has a high potential for success, when all power components and gate driver electronics are vacuumized and soaked in a proper dielectric fluid. This is valid for the individual components as well as for the complete circuits. Also the feedbacks from the components manufacturers are uplifting in that respect. So far the long-term switch-mode testing of the phase-legs are conducted in liquid environment at one bar pressure. The reason for that test of live power circuits are not conducted on pressurized circuits so far is lack of appropriate pressure chambers, including signal and power penetrators. The required pressure chamber will be available in the near future. In any case, the general statement from in-house insulating material expertise is that voltage withstandability should be expected to improve by increasing pressure.

A plan for various coating has been prepared in case problems are experienced during switch-mode testing or during PD testing, especially when the circuits are exposed to contaminated liquid. For the bonded IGBT modules, maintaining the normal gel used for standard components is also subject for evaluation. Therefore compatibility tests between such gels and various liquid candidates are subjects for investigations and experiments.
References


