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Pressure tolerant power IGBTs for subsea applications

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Keywords
Power semiconductor device, IGBT, Marine, Packaging, Insulation

Abstract
This paper discusses methods to adapt power semiconductors like IGBTs for subsea operation, in from 1 bar to high pressure environment, and presents tests done to demonstrate reliable operation. The paper has focus on three main challenges; the liquid dielectric and how to avoid air filled voids, where the highest electric voltage stress occur, and whether operation in liquid without gel influence on the switching. Different test approaches and test results presented show that IGBTs operate well with Midel® 7131 as dielectric media. Potential advantages and challenges of bonded and press-pack technologies are shown to be quite different.

Introduction
Future oil and gas development projects call for reliable power electronics in a wide power range from small and medium power supplies (0.1-100 kW) for electronics, actuators etc., to high power converters (0.1-100 MW) for variable speed drives. If critical components like power semiconductors, DC-link capacitors and drivers can operate with satisfactory reliability in high pressure environment, this will open up for the realization of quite new converter concepts. Instead of having thick, heavy and expensive one-bar vessels for converters and electronics subsea, the power electronic converter can be placed in a less expensive and more manageble pressure compensated vessel with significantly reduced weight.

This paper presents results from a joint research project (collaboration between research centre, university and industry), where the intention is to demonstrate the operability of critical power electronic components in high-pressure environments up to 300 bar. General challenges of subsea applications, test methods and adaptation of an IGBT driver are presented in [2]. From literature [3] the high pressure failure mechanisms are known as total permanent mechanical failure, changes in device characteristics and temporary reversible failure. These problems with electronics have been known for many decades [4]. The main focus of this paper is on how well power IGBTs can be adapted to high pressure applications by using a dielectric liquid and no gel or additional encapsulation as environment for the power semiconductor chips. Both bonded IGBT modules and
press-pack IGBTs are modified and subject to different tests. Their structures are quite different, and so are the advantages and challenges in high pressure applications.

Liquid insulation

Liquid insulation of the power electronics

For a complete power electronic circuit to be operable in environmental pressure corresponding to subsea depths of up to several thousand meters, the circuit need to be enclosed in some uncompressible and insulating material to protect the converter components both against mechanical damage and against flashover due to electric voltage differences. The insulation material should be applicable in such a way that voids are avoided, it should serve as a heat-spreading medium, and it has to be cost-efficient due to the large volume needed. With these specifications a liquid is the obvious solution.

It is considered important to have a dielectric liquid that is pure, without contaminations, have a predictable and uniform and stable structure, not likely to cause any chemical reactions or to change character for any reason. The power semiconductor chips are considered to be the most fragile component of the converter regarding electrical stress, contaminations like humidity, gases and solid particles, and also when it comes to mechanical stress on bondings of planar IGBTs. Thus the closer the dielectric liquid comes to the semiconductor chips, the better this liquid needs to protect against dielectric stress and the higher its requirements will be. Since the gel is normally protecting the chips, operation without gel requires special care to be taken regarding how the dielectric liquid handles the electric fields stresses at the chip surface. And since the liquid is moving the chips will be exposed to moving particles and contaminations in the liquid. The larger the liquid volume, and the more components covered in liquid, the more difficult it will be to keep the liquid pure and free from contamination. Keeping large liquid volumes clean during assembly and operation is a matter of cost and working procedures.

Selected liquid candidates for testing in power electronic converter

There are several dielectric liquid candidates available, e.g. mineral oils, silicone insulation oils, organic esters, and synthetic oils. Mineral oils are traditionally used in all kind of transformers, breakers and cables for heat transfer and insulation. Possible problems with mineral oils could be low flash points, high pour point and that it due to low moisture solubility will precipitate dissolved water during cooling. Synthetic oils are used instead of mineral oils when special properties are required, like fire-resistance, thermal stability or high dielectric performance [5]. Compared to mineral oils synthetic liquids have a simple and well-defined composition. By using synthetic liquids the characteristics can be chosen and will be more controllable than when using organic liquids.

For the tests presented here the ester Midel® 7131 [6] is chosen. This is a synthetic liquid with high breakdown strength [7] and low thermal expansion. This blend of ester has good high-temperature stability. Midel® 7131 is biodegradable and non-toxic to aquatic life. The breakdown voltage is presented as constant (~ 80 kV) for moisture levels up to 600 ml/m³, which is claimed to be very much better than mineral oils [6].

Also Silicone oil (200R 50 cSt) has been considered. Silicone oils are synthetic liquids, used in transformers. The silicone oils are hard to remove from other equipment, which causes practical problems. Two types of perfluor liquids recommended for semiconductor industry are considered for future tests; Galden® and Flourinert™. They offer substantially lower viscosity than the others, which might be very important for cooling capability. However, care must be taken to choose a product with sufficient high boiling temperature.
Chip protection and adaptation for pressure tolerant (PT) semiconductors

Chip protection from the manufacturer for control of electric field stress

The power semiconductors need special protection against environmental contamination and high voltage stress. The chips are normally protected by the manufacturer in different ways. The chips in a bonded IGBT module are protected by a layer of gel [8], and the chips in the press-pack IGBTs are protected against environmental contamination by the sealed housing and against voltage breakdown by SF₆ gas. Fig. 1 shows a cross section of a bonded IGBT module. It illustrates the field stress areas (A and B) of the chip surface, and shows typical dimensions of a 1200 V IGBT.

The manufacturers use different measures to reduce the field strength at the chip surface. An edge termination is applied to lower the electric field at the chip edge [8][9]. Along the vertical chip edge there is an equipotential surface at the same potential as the collector metal below the chip. This causes the total voltage drop, and the electric field stress, at the chip surface to be on top of the chip along the oxide layer between the edge of the emitter metal and the outer edge of the chip (Area A in Fig. 1). The chips are also equipped with guard rings to control the electric field on the top surface of the chip [8][9]. According to information from one manufacturer the voltage drops linearly within the inner 2/3 of this insulating edge (w2, typically 0.4 mm in a 1200 V IGBT). Thus, the field set up at the chip surface due to the voltage difference between the collector and emitter is distributed over a very small distance. This distance is of special interest when it comes to high voltage stress in IGBTs and the effect of contaminations.

Since the surface of a semiconductor is still very sensitive to high electric fields additional passivation is needed for protection against high electric fields. Often a passivation layer, in most cases Silicon Oxide (SiO₂), is applied directly to each chip in the factory before assembly in a module [10][11]. This passivation layer also protects the chip form its environment, e.g. against contaminations influencing on the flow of carriers inside the chip.

Fig. 1: IGBT chip details and typical dimensions of a 1200 V IGBT (photo detail of IGBT Type I).

Pressure adaptation and pressure testing of bonded IGBT modules

Two different bonded IGBT modules (Type I and Type II), rated 1200 V and 300 A, are modified and subject to testing in liquid. Modified components are delivered by the manufacturers without gel and with an open housing, as shown in Fig. 2. For pressure tolerance (PT) adaptation of the bonded IGBTs it is chosen to use these IGBTs without gel and to expose the naked chips to the dielectric liquid.

In standard IGBT modules the chips are covered with one or two layers of gel, as illustrated in Fig. 3. This gel might contain voids that when exposed to high pressure may cause mechanical stress on e.g.
the packaging and bondings. Pressurisation of the standard IGBT Type I (with both soft and hard gel) in nitrogen gas up to 100 bar, resulted in mechanical deformation and complete damage. Without any modification the base plate was bent, the hard cover cracked and the gel squished out. Another pressure test was done with the same IGBT with holes in the hard cover to able the liquid to penetrate into the area between the hard and the soft gel. With this small modification there were no signs of electrical or mechanical degradation due to pressurisation in Midel® 3171 up to 300 bar for 61 days.

Thus, an alternative and simple way of pressure adaptation is to open the package and let the dielectric liquid flow into the module. The success of this method will depend on the gel to be without voids. There is also a risk that the gel will be dissolved by the liquid. The gel of the IGBT Type I, however, showed no sign of dissolving in Midel® 3171 during the 2 months preliminary tests at 300 bar. With a silicone liquid the silicone gel will be dissolved, but even with a good compatibility between gel and liquid some dissolving is expected during very long term operation at high pressure.

**Coating alternatives for protection of the bonded IGBTs**

Different alternative ways of pressure adaptation have been considered in case it becomes necessary to protect the chips better. The most promising alternative is to add an additional protection layer directly on top of the chips as an enforcement of the passivation layer inside the chips. For this purpose Parylene™ C [12] is considered as a good candidate [13]. Parylene is used for protecting electronics in difficult environment. It uniquely coats all exposed surfaces with a thin uniform coating layer. Other possible coating materials are silicone, polyurethane and epoxy.

Another alternative is to keep the gel and to add an additional layer of coating on top of the gel to prevent the gel from reacting with the liquid dielectric. This top coating material should cover components or areas completely in order to avoid contact between gel and liquid. It should be flexible, and it should not react with gel or liquid, in order to keep the gel in place even when exposed to different pressure and temperature. For this purpose materials like Parylene™ C with a glass-like consistency will probably not be suited, since it provides no mechanical support and is not able to immobilize the gel.

**Pressure adaptation of press-pack IGBTs**

Several press-pack IGBT test samples are acquired for testing different options for pressure tolerant solutions. The standard module, rated at 2500 V and 360 A, consists of five IGBT chips and two diode chips (see Fig. 6) and is filled with SF₆ gas. One of the modified samples is a pre-clamped phase leg with two modules. These modules are without SF₆ gas. They are open, with a slot all the way around the collector contact plate to allow liquid filling. Fig. 4 shows a cross section of an open module. One modified component is an open mechanical sample, to be further adapted in our laboratory for liquid filling tests. Finally separate IGBT and diode chip assemblies are delivered from the manufacturer.

From the separate chip assemblies both a single diode test object and a single chip phase-leg converter have been built for different tests. The complete phase-leg converter shown in Fig. 5a is composed of one (lower) IGBT chip, one (upper freewheeling) diode chip, a dc-capacitor and a gate driver in a specially made assembly designed to fit in a pressure chamber. Fig. 5b shows an illustration of the single chip test object that is used both with a live diode and with the chip replaced by a dummy. All PT adapted objects are made for use in liquid, with no additional protective encapsulation.

![Fig. 4: Cross section of the press-pack switch, showing one IGBT chip and two diode chips.](image-url)
Tests and test results

Vacuum filling test of press-pack IGBTs

One challenge when considering press-pack IGBTs is liquid filling, and how to replace all the gas/air pockets inside the module with dielectric liquid. The dielectric liquid has only a narrow path for penetrating into the module and under the chip assemblies (highlighted in Fig. 4). The narrow passages between chips and support stand (5 in Fig. 5b) inside the module represent the critical points in the press-pack structure. Vacuum filling tests are performed to verify how efficient liquid penetrates into these critical areas. The vacuum filling technique is used in several applications as in resin filled transformers. For these tests a mechanical sample has been specially modified with a top transparent window, as shown in Fig. 6. The same adaptation has been done to two of the chip assemblies (one diode and one IGBT) inside the module. The transparent windows replace the original upper contacts and chips (1 – 4 in Fig. 5b) and allows a visual inspection of the inside part of press-pack module.

The press-pack chip assembly was vacuumized down to 0.5 mbar and gradually filled with coloured (pink) Midel® 7131. The filling process, that was visual inspection and video taped from the top window of the module, was successful. No voids have been detected, and it is shown that the oil was able to fill every air cavity in the inner parts of the module.

Dielectric tests of diode chip assembly in dielectric oil

The press-pack chips are designed for operating in SF₆ gas environment. With the chip assembly in oil the electric field has a different distribution; this requires proper testing to ensure that the electric
fields can be tolerated by the structure. By applying a reverse bias voltage to the diode a worse case condition concerning the electric fields is considered.

The single diode chip object was tested with a reverse voltage up to 2.5 kV, which is the nominal rated voltage of the diode. The voltage was applied with 100 V steps every 5 minutes. No failures were detected and the diode leakage current was in the range of μA, as shown on Fig. 8. No reference data was available from the manufacturer for this parameter; however, the value seems to be reasonable for a diode chip rated at 180 A and 2.5 kV. The graph shows small non-linearities in the measured current for reverse voltages between 1000 V and 1800 V. No explanation was found for this phenomenon.

The single chip object was also tested to verify whether the electric fields in the chip assembly cause any electric discharge. For this test the diode chip (2 in Fig. 5b) was replaced with two dielectric layers (Melinex®), and voltage up to 10 kV was applied between the two contacts. In air the modified chip assembly withstood 1.5 kV in repetitive tests, while flashover occurred at 2 kV. The same test was performed in oil and in this case the test was stopped at 10 kV without any flashover. This test indicates that the dielectric oil is a good replacement for the SF₆ gas.

**Single chip press-pack IGBT switching in liquid**

The single chip press-pack phase-leg converter (Fig. 5a) has been tested both in air environment and submerged in Midel® 7131. To avoid temperature raise of the chips the initial testing was performed as double-pulse testing, with two short on-pulses followed by a 1 second off-period with no current flowing, as illustrated in Fig. 8. First the converter was tested in air with the voltage limited to 200 V and a maximum transistor current of 130 A. The current rating of this IGBT chip is 72 A (144 A peak). The same tests were also performed in Midel® 7131 at 1 bar. The PT single chip converter is shown to operate well both in air and liquid environment. The switching waveforms show no relevant difference between operation in liquid and in air, as shown in Fig. 9.

**Fig. 7: Diode leakage current (μA) as function of voltage.**  **Fig. 8: Double pulse switching waveforms.**

**Fig. 9: Press-pack IGBT chip turn-on (left) and turn-off (right) in air (pink) and liquid (blue) at 25 °C.**
Bonded IGBT switching in liquid

Both types pressure tolerant (PT) bonded IGBT modules without gel, are tested in Midel® 7131. A complete phase-leg converter, including a PT IGBT module, drivers and dc-capacitor is placed in a glass container with liquid, as shown in Fig. 10. The IGBT Type II has been exposed to the liquid for more than 7 months. Measurements are done on standard components, with gel, in air environment for reference. The PT components are tested in air up to 50 V and in liquid up to 600 V and 400 A.

The measurements on the Type II IGBT show no significant effects of the PT adaptation and the operation in liquid. The same PT module operated in air and in liquid show nearly the same switching waveforms, as shown in Fig. 11 (turn-off of 95 A at about 50 V). There are also no changes in the switching waveforms during the first five months the PT module has been exposed to liquid (from September 2008 to February 2009), as shown in Fig. 12. The left part of this figure shows turn-off measured at four different times. Comparing the reference component (standard with gel) in air environment to the PT module in liquid, as in Fig. 13 and 14, show some difference that most probably is because these are different components (of the same module type, but different production week). It is observed that the differences between the waveforms are larger at high temperature (80 °C) than at low temperature (25 °C).

Fig. 10: Converter bridge-leg in Midel® 7131.     Fig. 11: Turn-off PT (I) in air (pink) and liquid (blue)

Fig. 12: Turn-on waveforms from September 2008 to February 2009 (blue) at 25 °C.

Turn-on 200 V and 100 A (two curves)

Turn-off 400 V and 200 A (four curves)
Fig. 13: Turn-off of 600 V and 400 A at 25 °C and 80 °C (right). Reference (blue) and PT (pink).

Fig. 14: Turn-on of 600 V and 200 A at 25 °C and 80 °C (right). Reference (blue) and PT (pink).

Fig. 15: PT Type II in air (pink) and liquid (blue) at 50 V. Turn-on 8 A (left) & turn-off 16 A (right).

The PT Type I IGBT module is also tested both in air and in oil, at low voltage (50 V) and low current. These measurements, Fig. 15, show no significant difference between operation in air and in oil. A difference in the frequency and damping of the current oscillations in turn-on is observed. This difference could be due to changed capacitance between the bonding wires because of the liquid, or due to temperature and cooling conditions. This will be subject for further investigations.
Testing electric field stress and protection needs of semiconductor chips without gel

When the gel/SF₆ is removed and alternative insulation and chip protection is discussed, knowledge about where the maximum electric fields appear at the chip surface, and about the properties of the new insulation material in this specific application becomes very important. Similarly knowledge about potential contaminants and their effect on both voltage stress and switching behaviour is needed. The field strength in the area A of Fig. 1 is of special interest when the gel is removed. Exact simulation to determine this field will be too complicated since it will require exact knowledge about the internal chip features, e.g. the guard rings. Thus, experimental tests on IGBT will be performed as a part of a newly started PhD work [2].

Another voltage stress area of the IGBT is over the substrate (area B in Fig. 1) [14]. At high voltages it is reported that partial discharge (PD) can take place at the interface between the ceramic and the silicone gel and at the rim of the copper metallization due to high electric field [15]. PD in gel are studied in [14] showing that the gel has similar PD properties as liquid, but with the main difference that gel degrades and have limited self-healing capability. It is also shown that increasing the temperature increases both PD charges and number [14]. The PD properties of the new insulation material replacing the gel, needs to be investigated for conditions comparable to what will occur in an IGBT module. This has been started as an activity at SINTEF/NTNU [15] and as a PhD work [2]. Tests in Midel® 7131 show that streamers may be initiated by sudden switch-off of dc pre-stress [15].

Streamer initiation and propagation on the chip surface

It is part of the requirement that the equipment shall operate from 1 to 300 bar. According to previous tests done on streamers in transformer oil [16] the stresses due to high electric field strengths will be larger at one bar than at higher pressure. In [16] it is shown that the length of streamers decreases with increasing pressure. This is assumed to be mainly because streamers are created by channels filled with gas or plasma that are maintained by an internal gas pressure, and thus will be compressed due to increased pressure. From this it is assumed that the effects of the field stress will decrease as the pressure increases. Thus, the effects of field stress should be tested at 1 bar.

Future tests

Future test will focus on operation at high pressure, long term operation at high temperature, and on effects of contaminations. Tests of the bonded IGBT Type I in contaminated liquid have started. Due to delay of delivery of pressure vessel for testing live power circuits, live operation at high pressure has not been tested yet. Such tests will be done this year, with a gradually increasing pressure. The press-pack single chip phase-leg converter will be the first operating at 300 bar.

Presently the converter containing the bonded IGBT Type I module without gel is subject to long term testing in Midel® 7131. This test is run at 600 V, switching 200 A at 5 kHz semi-continuously at high temperature. The transistor is switching when the heat-sink temperature is between 50 °C to 80°C, then the transistor is turned off until the heat-sink and liquid has cooled down to 50 °C. The switching period is about 2 - 3 min and the off period is about 20 min. Current, voltage and different temperatures are logged.

Conclusion

Different methods to make bonded and press-pack IGBTs pressure tolerant are discussed. It is chosen to remove the original insulation material (gel or SF₆ gas) surrounding the chips and to allow the same dielectric liquid into the IGBTs as used for the rest of the converter. A future alternative option is to add an additional protection layer of Parylene™ C directly on the chips for protection against contaminations in the liquid. With the narrow spaces inside a press-pack IGBT it is a challenge to be able to fill it completely with liquid. This is shown to be successful using a vacuum filling technique.

Electric tests on three different IGBTs without gel/SF₆ are performed in Midel® 7131 at 1 bar, showing switching performance, voltage breakdown and leakage current. Switching tests and dielectric tests
show no significant effects of replacing gel/SF$_6$ with Midel® 7131. All IGBTs operate well in liquid at 1 bar.

High ambient pressure is applied to test the mechanical effects on both standard and PT adapted components. Opening the housing to allow the liquid to penetrate into the components is shown to be enough to prevent mechanical damage. After 61 days at 300 bar the gel covering a standard bonded IGBT shows no sign of dissolving in Midel® 7131.

Long term and high temperature effects of operation in liquid will be subject to future tests. Electric switching tests are planned in ambient pressure up to 300 bar. And the ability of the new dielectric material to protect the chips against voltage breakdown and environmental contaminations will be subject to further testing. The breakdown strength of the liquid is expected to improve with increasing pressure [16], thus many tests can be done at 1 bar.

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