Pressure-Tolerant Power Electronics for Deep and Ultradeep Water

R. Pittini and **M. Hernes,** SINTEF Energy Research

Summary

This paper presents results from an ongoing research project (SINTEF 2011) on pressure-tolerant power electronics. The main goal of the research is to provide and demonstrate solutions that enable power-electronic converters to operate in pressurized environments. Oil companies have plans for subsea processing of oil and gas. Today's concept considers power-electronic converters in 1-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 owing to improved heat conduction through the vessel walls. The new concept considers power-electronic converters placed in vessels completely filled with appropriate dielectric liquid able to operate at pressures from 1 bar up to several hundred bar. Dielectric fluids are required to prove their properties, especially those related to insulation, incompressibility, and heat transport. The methodology presented here considers a mechanical adaptation of components followed by various laboratory experiments for verifying or correcting the proposed solutions (Pittini et al. 2010; Hernes and Pittini 2009; Petterteig et al. 2009).

Standard off-the-shelf components and special pressure-adapted components have been subjected to various provocative pressurization 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 insulated gate bipolar transistor (IGBT) modified for operation at high pressure. Measurements performed at different pressures demonstrate that there is no relevant difference in terms of electrical parameters between this modified IGBT and a standard IGBT. Long-term tests proved the concept's validity. The next step will be to test bonded IGBT technology in a high-pressure environment, and finally, we will realize a demo converter 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 off the coast of Norway. To reduce 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 few kW [valve actuators and uninterruptable power supply (UPS)] up to tens of MW for variable-speed drives for oil pumps and gas boosting. Today's installations are based on concepts where power-electronic converters are assembled in 1-bar vessels. One example of such an installation is the Ormen Lange field in the North Sea, which has a design depth of 1100 m and a converter rating of 12.5 MW (Henri et al. 2010). As the converter power rating and the design depth increase, the vessels become increasingly bulky and heavy because of the high wall thickness required for coping with the pressure difference. Pressure-balanced vessels will significantly reduce this weight. Moreover, the cooling system for removing converter heat losses may become more reliable and less complex because the heat can be more easily conducted through the thinner vessel walls instead of by separate heat exchangers. Therefore, the oil and gas industry has shown an increasing interest for pressure-balanced solutions.

Only a few scientific publications discuss pressure-tolerant power electronics, and most of these are outdated owing to new encapsulation and material technologies (Barnes and Gennari 1976; Gilbert et al. 1980; Holzschuh 1977; Snary et al. 2003; Marquardt 1978; Gilbert 1973; Sutton 1979; Holzschuh 1974; Gilbert 1974). 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 direct-current (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 upon. One reason is that open results from international research on pressure-tolerant electronics are more accessible than those for power electronics. Another reason is that converter control electronics can be easily separated in pressure-compensated and relatively small stand alone units with a tidy interface (fibers, for instance) 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 and three identical phase legs with a common DC-link capacitor bank (Mohan et al. 2003). Therefore, the converter selected as a test object for most of the live experiments in the present research consists of a phase leg with free-wheeling diode (FWD), IGBT, gate driver, and one or more DC-link capacitors. Such a test circuit will represent single-phase as well as three-phase and multiphase PWM converters.

Selected and Tested Components

Operation of power-electronic converters at sea depths of thousands of meters requires that power-electronic circuits be enclosed in a vessel filled with an incompressible medium with the appropriate insulating characteristics (a liquid dielectric medium). It is essential that the chosen dielectric liquid be applicable in such a 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 should be relatively cost effective because large volumes will be required. Already established and well-proven liquids used for other electrical 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 because of its high breakdown voltage, good tolerance to high moisture levels, low cost, good high-temperature stability, and its nontoxicity and biodegradability (M&I Materials 2011; Larsen 2007).

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 subjected to investigations. The housing should allow complete liquid filling of any voids

This paper (SPE 154399) was accepted for presentation at the Offshore Technology Conference, Houston, 2–5 May 2011, and revised for publication. Original manuscript received 1 July 2011. Revised manuscript received 22 August 2011. Paper peer approved 27 September 2011.

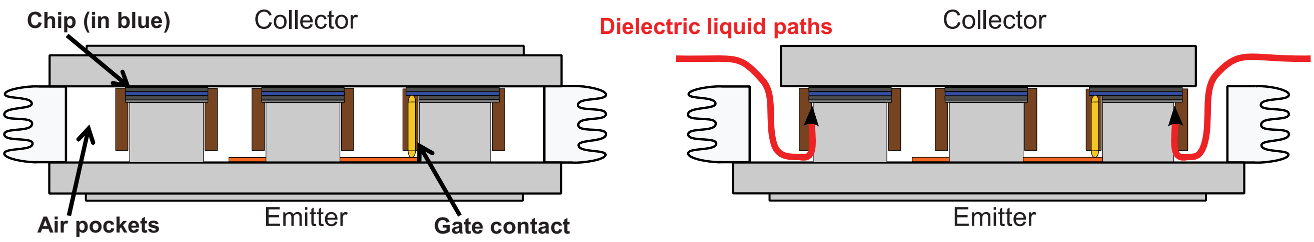

Fig. 1—Structure of an off-the-shelf press-pack IGBT (left) and concept for adaptation to pressure tolerance (right).

inside the components. In addition, special coating materials have been considered as possible additional sealing and protection layers, 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 subjected 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 analyzed and tested. The present paper, however, discusses only the press-pack alternative because this was found to be most challenging regarding adaptation for pressure tolerance, and because the press-pack design has so far been subject to the most live testing at high pressure. From the different candidates for the DC-link power capacitor, film capacitors were chosen as main test objects by the criterion of good data on energy density and lifetime. Off-the-shelf and custom-designed capacitors from three manufacturers have been analyzed and tested. Two IGBT gatedrivers were investigated for pressurization: a commercial high-voltage gatedriver and an in-house-developed driver.

Initial Pressurization of Standard and Modified Components

After the initial analysis, the test program 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 more easily 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 seconds) 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 to the component or the housing. The same test also proved that modified housings or specially designed or modified components can relieve the pressure stress, and 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. 1)** and the other was the bonded planar module **(Fig. 2).** Standard press-pack IGBTs are built by paralleling of several IGBT and FWD chips. A standard press-pack IGBT has a sealed housing filled with SF_6 gas. Its structure, and a way to pressure adapt it, is shown in Fig. 1. 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. The separate chips, without the press-pack housing, were delivered by the manufacturer. The component used as reference is the standard 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 at 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.

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-second off-period with no current flowing, as illustrated in **Fig. 3.** Continuous switching tests were performed applying reduced current because of the limited cooling capabilities of the designed phase leg. Both tests use the same circuit topology **(Fig. 4).**

A pretest of the phase leg was performed in an 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 a vacuum technique. The initial tests with reduced DC-link voltage and current verified that there was no difference

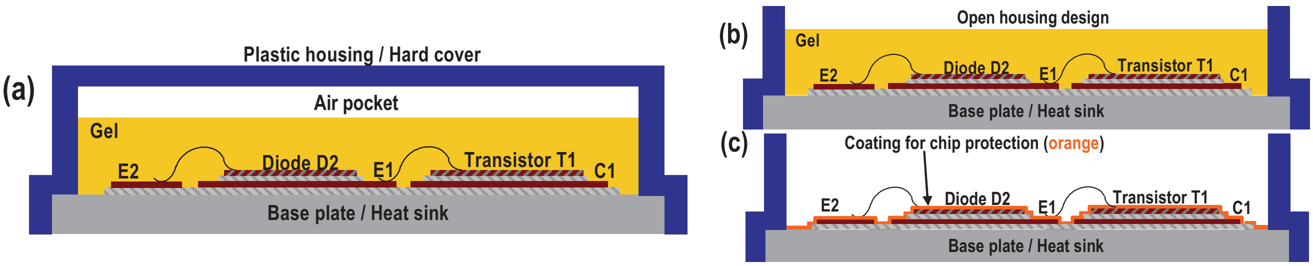

Fig. 2—(a) Common structure of planar IGBT with internal air pocket, (b) concepts for adaptation to pressure tolerance with open IGBT housing with original gel, and (c) with special coating layer for protection of power semiconductor chips.

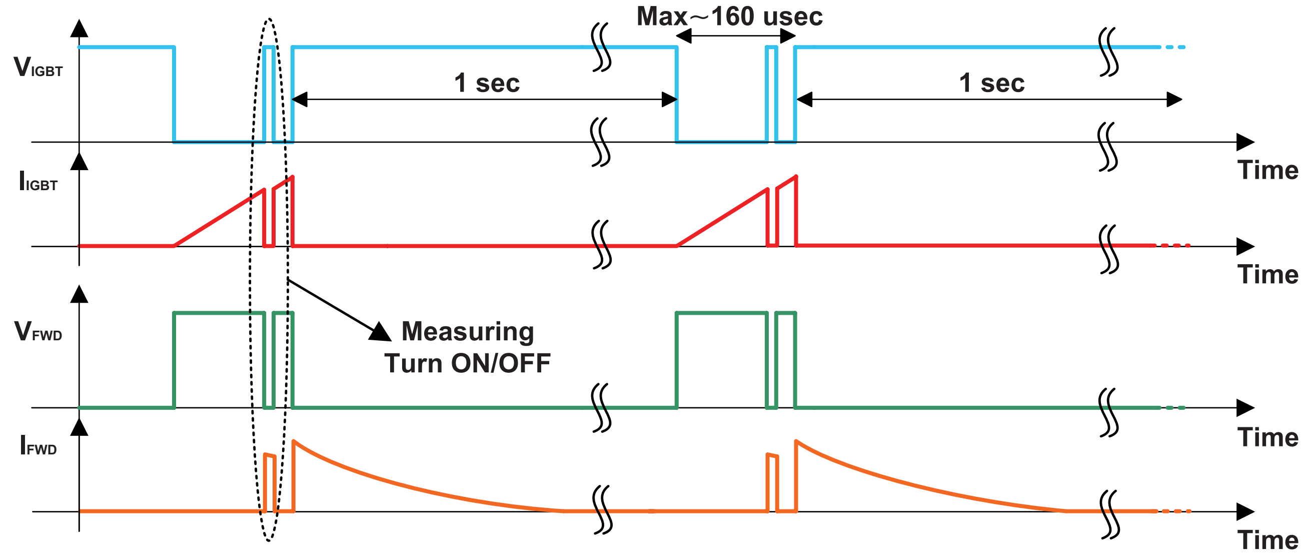

Fig. 3—Double-pulse-testing waveforms.

in the switching waveforms between the phase-leg operating in air or in the selected dielectric medium **(Fig. 5).** Operation at 1 bar is expected to be the most critical in terms of voltage breakdown because the breakdown strength of the liquid improves with increasing pressure (Larsen 2007). During the 1-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. 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 by 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 because, when the phase leg was operated continuously, it generated heat that caused 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 ran until February 2011. At that time, the test object was taken out of the pressure chamber and subjected to various post-test examinations.

Presentation of Test Results

During initial tests, the phase leg was tested with DC-link voltages above 1 kV **(Fig. 6).** With the phase leg inside the pressure vessel, the DC-link voltage had to be limited because of 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 performed up to 300-bar hydrostatic pressure **(Table 1).** 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

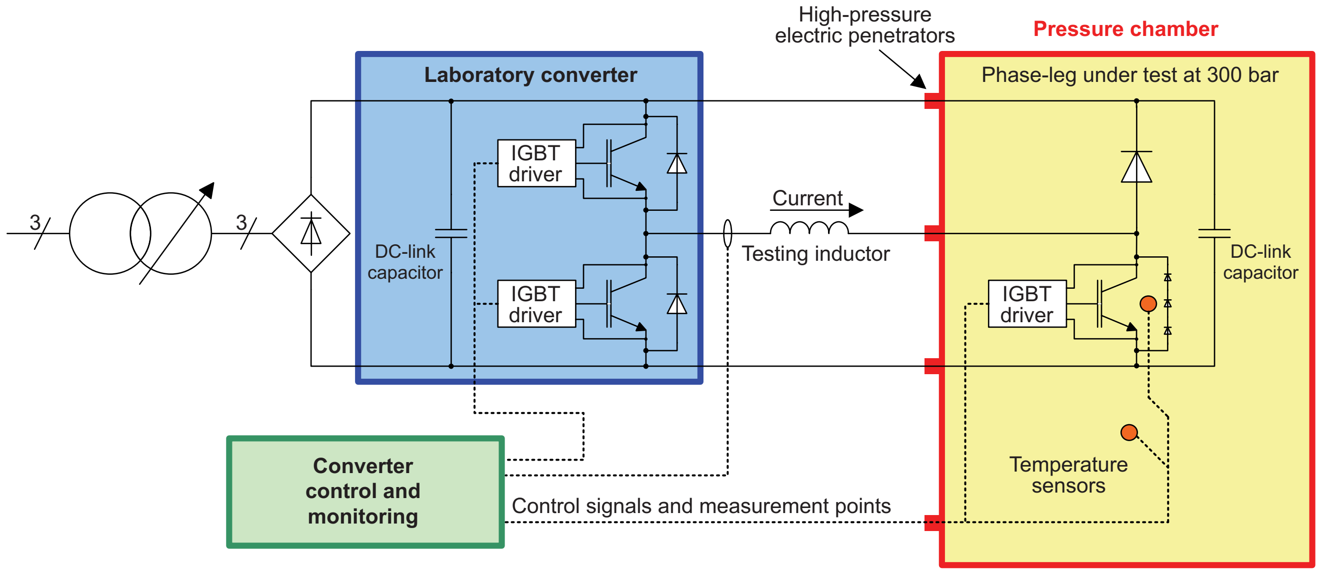

Fig. 4—Test-circuit diagram including the test object with devices under test (FWD and IGBT).

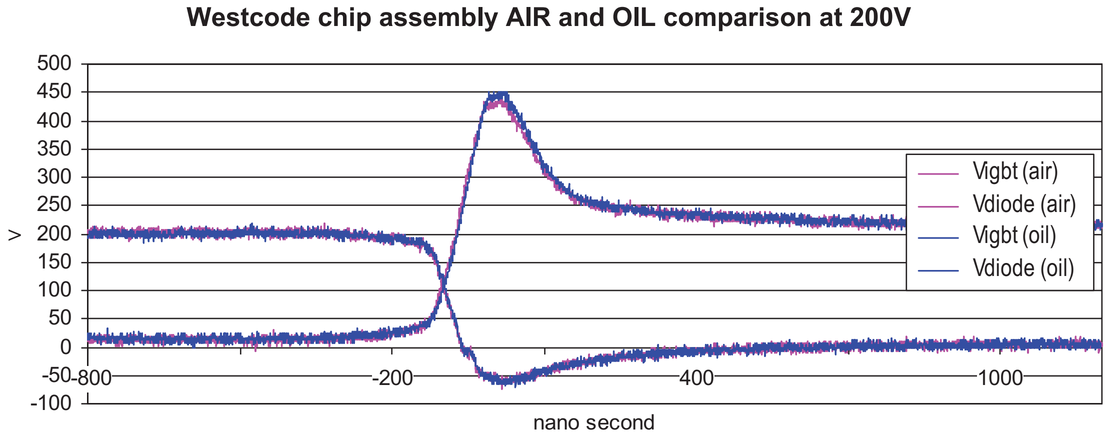

Fig. 5—Measurements of switching waveforms in air and in dielectric liquid (Midel®7131) at 1 bar.

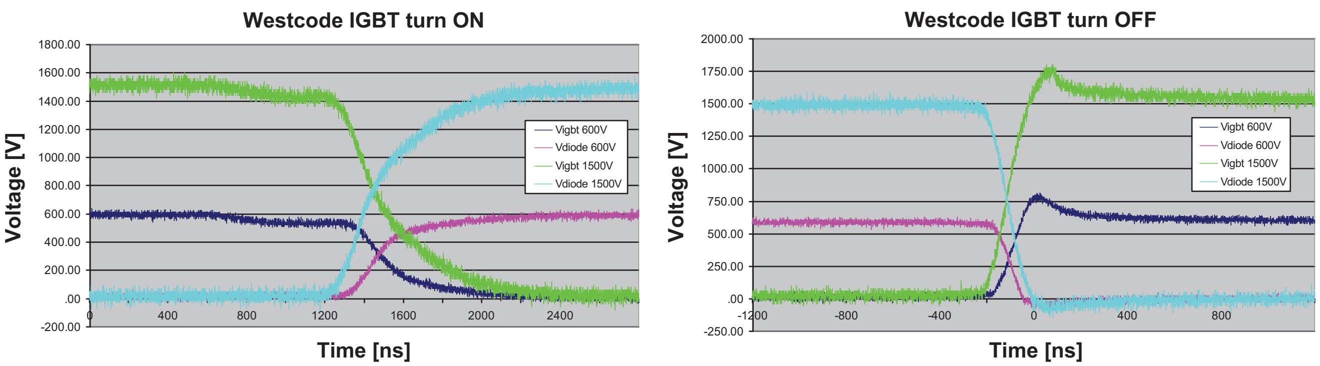

Fig. 6—Switching waveforms for the chip-assembly phase-leg up to 1.5-kV DC-link 1 bar.

TABLE 1—TESTING PRESSURES FOR IGBT PHASE LEG								
Testing Pressures (bar)								
1	10	30	50	100	150	200	250	300

to 100 bar (corresponding to ~100 kgf per cm^2) because, at this pressure, the components are already subject to large mechanical stresses. Measured data were stored and post-processed, allowing the scope triggering points to be aligned for the presentation.

IGBT turn-on and turn-off voltage waveforms are presented in **Fig. 7.** 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 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; the transistor turn-off tail is slightly moved leftward. 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 to 50 bar are shown in **Fig. 8.** 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.

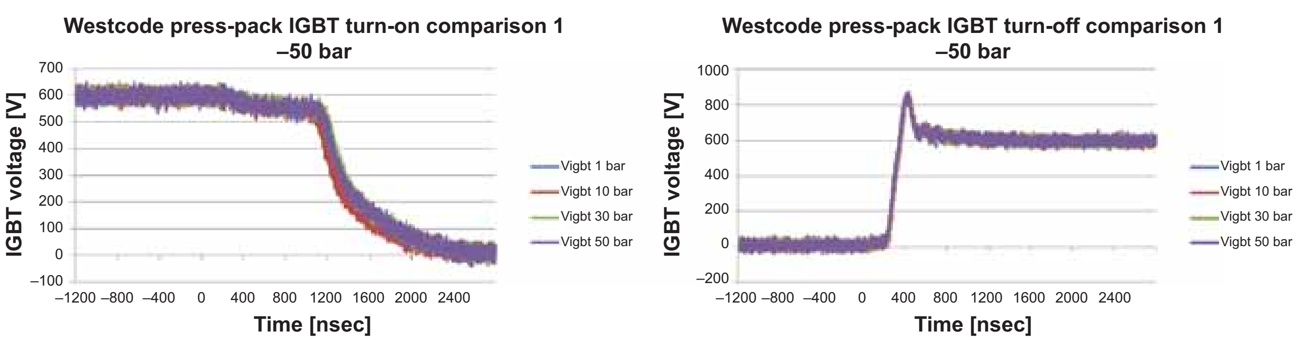

Fig. 7—IGBT turn-on and turn-off voltage waveforms at different pressures between 1 and 50 bar.

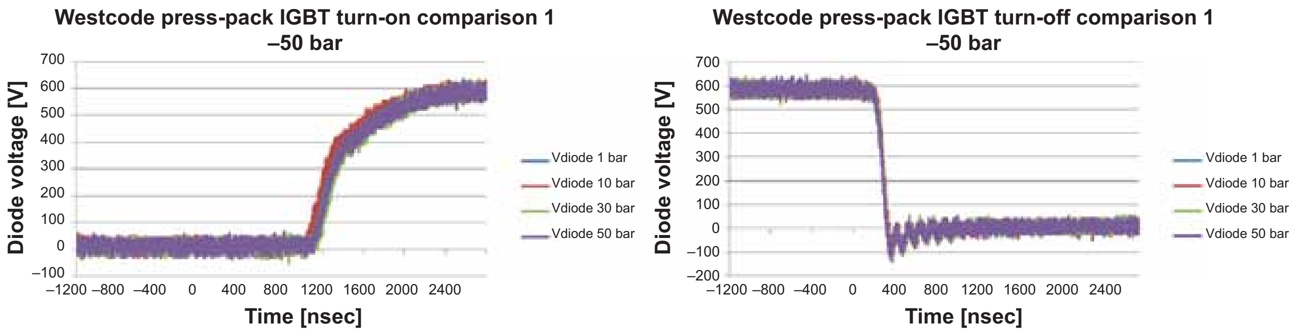

Fig. 8—FWD voltage waveforms at different pressures between 1 and 50 bar at IGBT turn-on/-off.

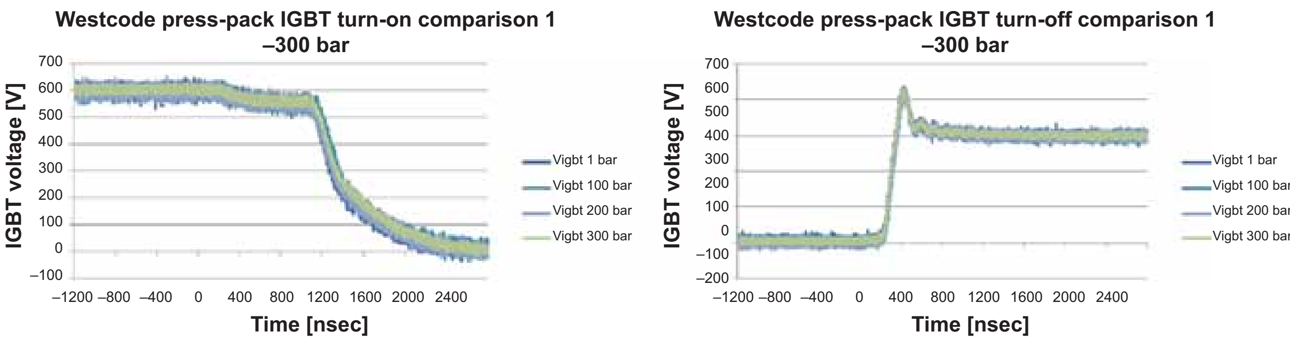

Fig. 9—IGBT turn-on and turn-off voltage waveforms at different pressures between 1 and 300 bar.

The complete pressure range between 1 and 300 bar is analyzed in the same way as described previously for the 1–50 bar range. IGBT and FWD voltage waveforms at turn-on and turn-off for different pressures are analyzed in **Figs. 9 and 10,** respectively. The analyzed 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 behavior of the specially designed chip-assembly phase-leg converter. This long-term test continued until February 2011, operating the converter at 600 V, 10 A, and with hydrostatic pressure of 300 bar. The current is low because of the limited cooling capacity of this test setup.

Bonded modules without gel were tested at 1 bar for approximately 1.5 years with good results. This is very encouraging. 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 (Larsen 2007). The chips will be directly exposed to any contaminations in the liquid. This can cause long-term issues, such as flashovers.

Late in 2011, similar tests were carried out for planar, bonded IGBT modules with gel.

Conclusions

Pressure-tolerant power-electronic converters have the potential of 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 testing of individual components with no voltage applied has confirmed the critical encapsulation 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 electrical characteristics in the 1- to 300-bar operating range. The tested converter included IGBT and diode-chip assemblies,

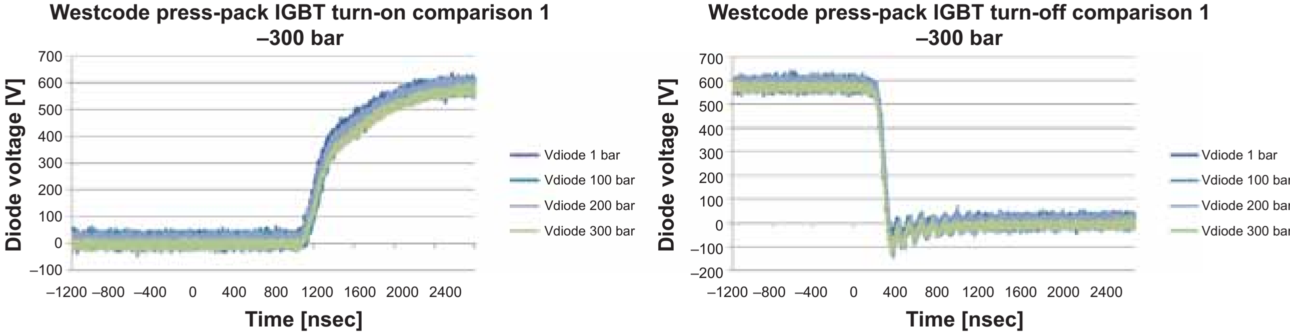

Fig. 10—FWD voltage waveforms at different pressures between 1 and 300 bar at IGBT turn-on/-off.

a power capacitor, and a 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 3 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 close proximity to the IGBT and diode chips where the electric-field strength is very high. New ideas have emerged during the test program about how to improve encapsulations for liquid-isolated components, especially in preventing contaminants from accessing the chip. Continuing activities are proposed.

Acknowledgments

This paper presents results from a research project (SINTEF 2011) financed by the Norwegian Research Council (the PETROMAKS Programme) and industry partners (EXPRO, Petrobras, StatoilHydro, Total, Siemens, Aker Solutions, and Wärtsilä), and with NTNU as university partner. Thanks to component manufacturers (IXYS, Tyco, Westcode, ICW, and EPCOS) for excellent service in supplying test samples and expertise during the project.

References

Barnes, H.E. and Gennari, J.J. 1976. A review of pressure-tolerant electronics (PTE). Final Report, AA/AB, Naval Research Lab, Washington, DC (June 1976).

Gilbert, D.E. 1973. Ion contamination and pressure tolerant electronic systems. *Proc.,* IEE International Conference on Engineering in the Ocean Environment (OCEANS '73), 25–28 September, 273–278. http://dx.doi.org/10.1109/OCEANS.1973.1161208.

Gilbert, D.E. 1974. Transistor Cutoff Characteristics in Oils. *Proc.,* IEEE International Conference on Engineering in the Ocean Environment (OCEANS '74), Halifax, Nova Scotia, Canada, 21–23 August, Vol. 2, 179–184. http://dx.doi.org/10.1109/OCEANS.1974.1161409.

Gilbert, D.E., Manes, E., and Allard, F.C. 1980. Analysis of the Performance of a Pressure-Tolerant Light-Emitting Diode/Fiber Optic Cable Interface. *Proc.,* OCEANS '80, Seattle, Washington, USA, 8–10 September, 440–444. http://dx.doi.org/10.1109/OCEANS.1980.1151370.

Henri, B., Truls, N., and Terence, H. 2010. Ormen Lange Subsea Compression Station pilot. *Proc.,* PCIC Europe 2010 Conference Record, Oslo, Norway, 15–17 June, INSPEC 11446893, 1–9.

Hernes, M. and Pittini, R. 2009. Enabling Pressure Tolerant Power Electronic Converters for Subsea Application. Paper presented at the 13th European Conference on Power Electronics and Applications (EPE'09), Barcelona, Spain, September 2009.

Holzschuh, J.E. 1974. Pressure Tolerant Electronics. *Proc.,* IEEE International Conference on Engineering in the Ocean Environment (OCEANS '74), Halifax, Nova Scotia, Canada, 21–23 August, Vol. 2, 190–194.

Holzschuh, J.E. 1977. Applications of Pressure Tolerant Electronics. *Proc.,* OCEANS '77 Conference Record, Los Angeles, 17–19 October, 729–734. http://dx.doi.org/10.1109/OCEANS.1977.1154321.

Larsen, S. 2007. *Streamer inception and propagation in transformer oil under hydrostatic pressure*. MS thesis, Norwegian University of Science and Technolgy (NTNU), Trondheim, Norway.

M&I Materials. 2011. MIDEL®7131 (data sheets), http://www.midel.com/productsmidel.htm.

Marquardt, R.A. 1978. Five-Year Life Test Data on Pressure (10 000 lbf/in^2) Tolerant Electronic Components. *IEEE Transactions on Components, Hybrids, and Manufacturing Technology* **1** (4): 365–371. http://dx.doi.org/10.1109/TCHMT.1978.1135301.

Mohan, N., Undeland, T.M., and Robbins, W.P. 2003. *Power Electronics: Converters, Applications, and Design*, third edition. Hoboken, New Jersey: John Wiley & Sons.

Petterteig, A., Pittini, R., Hernes, M., and Holt, Ø. 2009. Pressure Tolerant Power IGBTs for Subsea Application. Paper presented at the 13th European Conference on Power Electronics and Applications (EPE'09), Barcelona, Spain, September 2009.

Pittini, R., Hernes, M., and Ljøkelsøy, K. 2010. An IGBT Gate Driver for Operation in High Pressure Hydrostatic Environment. Paper presented at the PCIM Europe 2010 International Exhibition & Conference, Nuremberg, Germany, May 2010.

SINTEF. 2011. Electric power systems for subsea processing and transportation of oil and gas. KMB Project Application to The Research Council of Norway. Part of the Power Supply to Subsea Installations project, SINTEF Energy Research, Trondheim, Norway, http://www.sintef.no/subseapowersupply (27 January 2011).

Snary, P., Bingham, C.M., Stone, D.A., and Schofield, N. 2003. Drive Systems for Operation on Deep-Sea Rovs. Paper presented at the 10th European Conference on Power Electronics and Applications (EPE 2003), Toulouse, France, 2–4 September.

Sutton, J.L. 1979. Pressure Tolerant Electronic Systems. *Proc.,* OCEANS '79, San Diego, California, USA, 17–19 September, 460–469. http://dx.doi.org/10.1109/OCEANS.1979.1151321.

Riccardo Pittini is a PhD candidate in power electronics at the Technical University of Denmark. Previously he held a research scientist position at SINTEF Energi AS, Trondheim, Norway. He has expertise on pressure-tolerant mid-high power converters, and converter components for subsea applications. His current research interests are subsea and offshore power electronics, converters for fuel cells and electric mobility, renewable energies, high-temperature power electronics, power-converter circuits, IGBT gate drivers, and embedded systems. He holds BSc and MSc degrees in electronic engineering from the Università degli studi di Udine, Udine, Italy. **Magnar Hernes** is a Senior Research Scientist with SINTEF Energy Research, where he has been employed since 1979. He has broad experience from development of power electronic converters for the industry (e.g., UPS, variable speed drives, and special converters for electrical vehicles and subsea hyperbaric welding machines). He has also experience in analysis of complex power systems comprising power electronics for the oil and gas industry. He has also conducted several research programs within power electronics, for instance power electronics for grid integration, power electronics for renewables, and pressure-tolerant power electronics. He holds an MSc degree from the Norwegian University of Science and Technology.