Setting a course for subsea power conversion
Working with industry partners, ABB has developed a subsea power system for the oil and gas industry that is more advanced than probably any other system of its kind. Outfitted with a pressure-compensated variable speed drive, the system is now about to complete its equipment qualification process – a step toward subsea facilities with integrated drives for pumps and compressors.

As the oil and gas industry seeks to exploit offshore resources with ever-increasing efficiency, a tantalizing idea has surfaced: What if all the electrical equipment needed for driving and controlling subsea pumping and compression equipment could be located on the sea floor in the immediate proximity of gas compression and oil pumping stations?

Traditionally, such power systems have been stationed onshore or on topside facilities at sea. But if located on the sea floor, they would save space and weight at topside facilities, vastly reduce cable costs, cut response time to variables at wellheads, and considerably reduce the cost of the power supply, while improving reliability and dramatically reducing maintenance costs.1

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In view of these advantages, ABB, Equinor, Total and Chevron are now concluding a joint industry project (JIP) that developed and tested subsea power distribution and conversion technologies. During the first part of the project a full-scale prototype variable speed drive (VSD) converter was built and tested in late 2017 for 1,000 hours in shallow waters. An ABB industry analysis indicates that this was the very first time a medium voltage drive was operated at 9 to 12 MVA for an extended period while submerged in a seawater environment.

A second test was recently completed. It was based on the use of a second drive characterized by a refined and improved design. Both drive
units were operated in parallel connection to reach higher power levels but with the addition in this case of subsea switchgear and controls to test the full subsea power system.

**Breakthrough technology**

ABB’s variable speed drives are the heart of the subsea project. These 50-ton behemoths drive nearby electric motors for pumps and gas compressors. Modular in design, the VSDs can operate a wide range of subsea motors, ranging in power from 0.5 to 18 MVA, with voltages from 2.0 kV to 7.2 kV and the capability to drive conventional speed pumps and wet gas compressors rated at 50 – 120Hz, as well as high-speed gas compressors at up to 18,000 rpm directly at step-out distances from a few km to over 600 km.

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All of the VSD’s modules are designed to operate down to depths of 10,000 ft / 3,000 m or more and have been qualified according to API17F and SEPS 1002. One such qualification test included the operation of a power module with all its electronics and power components fully functional in a pressure vessel at 345 bar. The cell converted power up to 1,000 A for 3,000 hours in this high-pressure environment. This was one of the key steps for reaching technology readiness level (TRL) 4 – a milestone that opens the door to allowing oil & gas operators to employ the equipment in production fields.

The tank for the entire VSD utilizes a pressure-compensated design, which effectively removes limits as to the depth of deployment. Pressure compensation is achieved by submerging the drive hardware, including the drive transformer, in a dielectric liquid that also acts as a coolant. The drives’ electric power components, including capacitors, semiconductors and control electronics, are designed with enhanced safety margins, redundant hardware, and pressure resistance, and their materials are chosen for compatibility with the dielectric liquid to achieve a highly reliable overall design. Guiding development of this system was a design philosophy that built on but also expanded on ABB’s subsea transformer technology. These robust, maintenance-free and exceptionally reliable transformers have been successfully deployed since 1999. Finally, ABB’s new VSDs are outfitted with a controller as well as a communication interface to topside. These two units are housed in a subsea replaceable electronic module.

**Deep dive**

In 2019 two VSDs were deployed in shallow water in a harbor in Vaasa, Finland for testing. As part of a full subsea power system, both converter units operated in parallel in order to demonstrate the highest needed powers.

During the shallow water test, the drives were operated for more than 3,000 hours (about 125 days) at a 22 kV input and 6.9 – 7.2 kV output voltage at different power levels. This confirmed that all components of the VSD system work properly together. In addition, the VSDs’ built-in redundancy system has demonstrated itself to enable fault-tolerance as intended by continuing to operate after intentionally disconnecting (and later reconnecting) some of the internal modules through topside commands.

**Why subsea conversion sets the pace**

As suggested earlier, the subsea concept offers many advantages over conventional topside solutions. As →02 illustrates, the latter require every motor to have its own cable, which may be many kilometers in length. Furthermore, in addition to locating the VSD on the topside, such solutions require a step-up and a subsea step-down transformer to manage cable losses [1].
On the other hand, a subsea VSD system can control multiple nearby compressors and pumps with a single step-out power cable of fixed frequency to the station. Several such concepts have been shown by oil majors, including the “subsea garden concept” [2] exemplified on page 44.

From the word go, it was therefore obvious to engineers that subsea deployment was the way to go →03. The only question was, what technologies would make it possible?

Despite the novel environment the VSDs would be exposed to and the need for virtually flawless reliability, it quickly became clear that not everything had to be developed from scratch. To largely remove limits to the depth of VSD deployment, project engineers knew that the device would have to be filled with a dielectric liquid similar to what’s used in any standard transformer, thus providing internal pressure transmission, cooling, and electrical insulation [3]. In this situation the tank enclosure can follow similar design rules as a classical transformer tank and does not need to have the capability to withstand as much pressure as some other systems. Instead, an ABB subsea bellow compensator system is used to ensure that internal and external pressure always remain nearly identical.

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So far, so good! But what proved to be particularly challenging was adapting the electrical and mechanical components of a VSD, such as capacitors, semiconductors, local electronics and wiring to withstand the full environmental pressure at deep deployment locations. Furthermore, it was essential to ensure that all components would be chemically compatible with the dielectric liquid and that the thermal architecture of the entire tank would ensure cooling even at maximum depth with the utmost reliability. These were the key novel aspects that were successfully addressed by the current project.
temperatures constant and low. This approach has been proven to be effective and works with perfect reliability at any sea water temperature, pressure and salinity, as the properties of water in these conditions are well established [5].

A modular answer to power demands
Another major engineering challenge that confronted project engineers was the very large range of power and voltage demands that VSDs will have to cope with, primarily with regard to booster and injection pumps, wet, and dry gas compressors, as well as smaller power applications, such as submersible and scrubber pumps.

Working with key industry partners, the project’s engineers determined a basis of design for variable speed-driven subsea equipment that includes the following key electrical specifications:

- 2.0 – 7.2 kV output voltage
- 0.3 – 15 MW motor shaft power
- 0 – 200 Hz, and for drives < 5 MVA to 300 Hz fundamental output frequency
- 11 – 33 kV input voltage
- 30-year mission endurance
- Sea water environment at 3,000 m, 0 – 20 °C water temperatures

Given the breadth of these specifications, it became obvious that since no single VSD fixed design could cover everything, a modular system would be the answer and that, more specifically, a cell-based drive topology would be optimal.

The topology chosen for the project comprises a basic power module (PM), referred to as a cell. Each cell’s voltage, as well as the number of connected cells, determines a VSD’s output voltage to a motor. The cell size, which is directly related to its current rating, is also the converter current rating.

In the first two built units, the cells were designed for a rating of 1,000 A. In order to optimize reliability, a careful trade-off between cell nominal voltage and cell count is necessary for a given output voltage class; a higher cell voltage would lower the cell count and complexity but also reduce the ability to have redundant cells. The trade-off also considers the complexity of the drive transformer.

They were extremely significant achievements because earlier efforts to create a subsea VSD technology required prohibitively heavy massive steel vessels to withstand the water pressure, resulting in difficulties with cooling despite the cold-water surroundings [4].

Naturally, ensuring that all components remain within specified temperature parameters is essential for system reliability and safety. With this in mind, project engineers came up with a passive cooling concept that quite simply employs the interface between the tank walls and the sea water to dissipate losses and thus relies exclusively on natural convection. In short, not a single moving part – always a potential cause of failure – is needed.

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The passive cooling system’s performance was analyzed in the full system during the shallow water test. Results demonstrated that the system’s temperature distribution inside the tank followed design expectations, meaning that temperature-critical components could be kept in a low temperature environment for maximum reliability even at higher power levels. In fact, the subsea converter places the electronics modules in a near ideal thermal environment. Its oil cooling keeps temperatures constant and low. This approach has been proven to be effective and works with perfect reliability at any sea water temperature, pressure and salinity, as the properties of water in these conditions are well established [5].

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The cell itself consists of two half-bridges of insulated-gate bipolar transistors (IGBTs), and an assembly of capacitor units for the DC link. The IGBT gate drivers are powered directly from the DC link, thus avoiding high voltage insulated control power supplies. Communication to the cell is by optical fiber from a control-and-measurement unit inside the tank.
Each cell is equipped with mechanical devices (disconnectors, bypass) designed to separate it from the main power circuit. This results in a fault-tolerant drive that can remain in operation even if the cell itself fails. The level of redundancy can be selected based on the number of cells installed in a VSD unit in excess of the minimum required for achieving the output voltage. The cell is thus not only a key building block of the subsea converter but also a complete functional subunit and thus a highly meaningful unit for qualification together with all of its subcomponents.

All in all, shallow water testing confirmed that ABB’s subsea VSD and all its components, including redundancy and passive cooling operated properly together up to a level of 1,000 A. The system has thus achieved its goal: technology readiness level 4 and is ready for deployment on the sea floor.

As indicated in \( \rightarrow 05 \), the inverter with its assembly of cells supplied by the drive transformer, is complemented by an output filter and an input protection unit designed to limit transients to levels acceptable to connectors, cables, and motor, while guarding against dynamic overvoltages on internal components, respectively. These three units have an inherent built-in flexibility, so that project-specific adjustments are engineered to work without need for requalification, since only identical internal subcomponents are rearranged. Thanks to this approach, the entire power voltage range can be achieved for a given project by simply selecting the right number of qualified units and assembling them as a drive. For higher output currents, two complete converter units, each designed for direct parallel connection, can reach powers of up to 18 MVA.