SUBSEA ELECTRIFICATION APPLICATIONS AND TECHNOLOGY QUALIFICATION RESULTS

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Abstract - The use of subsea processing equipment, which maintains, increases and accelerates oil and gas production, is now more and more widespread on offshore subsea oil and gas field developments. To meet the technical challenges of these developments, subsea transmission, distribution and conversion electrical equipment are developed through the Subsea Power JIP where ABB, Equinor, Chevron and Total are partners. In the first part of the paper, Equinor and Total will present the foreseen subsea processing applications to use electrical subsea transmission, distribution and conversion equipment. In the second part of the paper, ABB will present the subsea Medium Voltage Variable Speed Drive and Medium Voltage Circuit Breaker modules developed to enable subsea factory vision, then give the technology Subsea Power JIP qualification results and technology readiness level.

Index Terms — Subsea VSD, Subsea Circuit Breaker, Subsea processing, Voltage Source Inverter, Subsea transformer.

I. INTRODUCTION

Many of the existing offshore oil and gas installations are currently on declining production, requiring IOR measures to maintain production. These installations typically have limited space and weight capacity. Subsea electrical distribution and conversion can enable supply of power to subsea pumps and compressors with limited modifications topside.

Tie-ins to existing installations will be increasingly important for the industry moving forward. Many of the existing discoveries are not large enough to bear a standalone development. Subsea electrical power technologies can be an important tool to enable new tie-in, due to the limited modification need on the host. Also, in cases where several pumps or compressors are needed, the technology enables supply of all consumers by one cable.

In parallel with the development of subsea processing equipment, some Oil and Gas operators promote the vision of full subsea factory or subsea to shore development as the preferred way to enable cost-effective field development of more dispersed, deeper and smaller oil and gas fields.

Therefore, to realize their vision, these oil and gas operators decided to join their efforts on a JIP Subsea Power project [2] aiming to develop technology for Transmission, Distribution and Power Conversion for implementation of their future subsea solutions at greater distances and deeper waters.

II. OIL AND GAS FIELD DEVELOPMENTS

A. Subsea equipment's, environment, requirements and challenges

Subsea is an environment with no eyes, ears or hands on the spot, where maintenance is both extremely costly and limited by the use of Remote Operated Vehicles (ROV). In this context subsea equipment must have high reliability and shall be designed to last a minimum of 25 years [1].

Subsea equipment should be as compact as possible and modularized to facilitate individual installation or retrieval at sea without requiring heavy ships and cranes. Control modules should be separately retrievable from main power modules.

To allow their use on different oil and gas field locations and secure their reliability, they must be designed for installation in water depths up to 3000 m, temperature ranging from -2°C up to 25°C and with standardized and simple interfaces to other subsea equipment.

Unlike onshore transmission and distribution systems which are often based on a ring system where faults are easy to isolate, subsea transmission and distribution systems are point-to-point connections with a single transmission link, especially for long step-outs; this sets requirements for high reliability and availability.

B. Subsea processing applications

Existing offshore fields are depleting fast and the new coming fields are not easy to develop due to their reduced size or dispersed locations. Fields may also yield more challenging fluids. Therefore, new ways for economical subsea processing are being developed for subsea separation, electrical heating, subsea compression and multiphase pumping on the sea floor, which accelerates production and as well increasing its recoverable volume (Figure 1). All these solutions require power at the seafloor to drive the respective pumps and compressors.

C. Energy efficiency

Improving energy efficiency and reducing CO_2 intensity associated with production of hydro carbons are amongst the top priorities as of today.

The subsea electrification technology can be an enabler for supplying subsea boosting with power from shore. Also, subsea compression as a standalone technology requires significantly less energy compared to platform compression. The closer the compression is located to the source, the higher the efficiency. The conversion and distribution technology may be an enabler for subsea compression and pumping.

By placing the VSDs subsea, the electrical transmission will operate at a fixed frequency of 50 or 60 Hz, compared to a variable, and higher, frequency in case of topside/onshore VSDs. A case study for a specific use candidate showed that the electrical transmission losses can be reduced up to 50% by using subsea VSDs.

Subsea power distribution and conversion can play an important role in realizing un-manned faculties, both for all subsea solutions and in combination with un-manned topside installations. Reduction in manning/personnel and utilities required for topside offshore installation reduces the associated emissions from the oil and gas production.

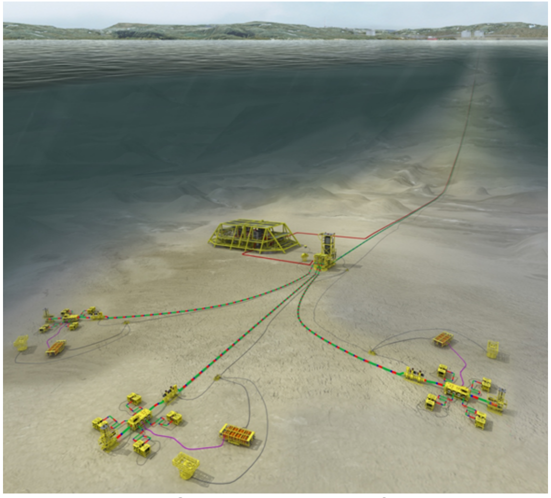

Fig. 1 Subsea processing facility

In these applications, subsea processing equipment can be linked to topside facility offshore or onshore either from new facility or brown fields.

D. Combined DEH and boosting

An interesting use case for the subsea electrification technology is combining power supply for Direct Electrical Heating (DEH) and pumping (Figure 2). This is particularly attractive for tie-ins to an existing host. In this concept, a single power cable is used to supply pipe heating and boosting. When the subsea pumps are running, there is no need for heating, hence the combined use does not lead to over dimensioning of the cable.

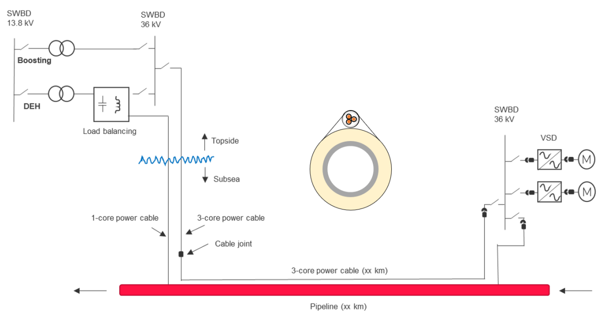

Fig. 2 Combined DEH and boosting

In pipe heating configuration, the three conductors in the cable are connected in parallel, operating as a single phase cable, while in pumping configuration it operates as a regular three phase cable. A subsea switchgear is used to switch between the configurations.

The solution gives minimal impact on the host combined with maximum utilization of the subsea power cable.

III. TECHNOLOGY DESCRIPTION AND QUALIFICATION STATUS

The base case for subsea power distribution covers the transmission of 100 MW power over distances up to 600 km to 3,000 m water depth. Power electronics and control systems would also be supported with 230/400 V.

Designing a power supply infrastructure that can operate at 3,000 m water depth for 30 years is a considerable challenge. Multiple significant technical challenges need to be overcome to achieve the exacting reliability required in the operational conditions specified above for such long periods of time. The inaccessibility of the equipment required fault tolerant approaches to assure the availability of the equipment. The pressure of the environment in these pressure-balanced subsea tanks is a new requirements on the electric components, and cooling needed to be of failsafe passive design. The found solutions are the result of a careful balance between novel and highly proven design approaches.

Started in 2013, the JIP project reached a major milestone in late 2017 when the first full-scale prototype of the variable speed drive (VSD) passed a 1000-hour shallow water test (SWT). Further, another major milestone was achieved in November 2019 when a full-scale shallow water test of the complete subsea power system with two VSDs in a parallel configuration combined with subsea switchgear and controls were successfully completed. Figure 3 shows the equipment being submerged into water for the 3000-hour test at the harbor test site in Vaasa Finland.

Fig. 3 Submerging of VSD (top photo) and switchgear (lower photo) for full-scale shallow water prototype testing at harbor facilities in Vaasa Finland in 2019

The JIP developed the following key products for subsea use:

- Subsea variable speed drive
- Subsea medium voltage switchgear
- Subsea control and low voltage distribution

The medium voltage subsea switchgear is required to distribute main power to subsea VSDs and other power consumers located on the seabed. The subsea switchgear can support up to six feeders including an incoming breaker, or a tie breaker to support cascading two switchgears. The incomer of the switchgear connects to the secondary of a subsea step-down transformer, or directly to a subsea power cable from topside/shore. The feeders connect to the subsea consumers, typically variable speed drives for seabed pumps and subsea compressors. The switchgear rated phase-to-phase voltage is 36 kV and main bus bar current is 1600 A. A modular and scalable concept accommodates a range of system cases and configurations, covering conventional 50/60 Hz but also LFAC 16 2/3 Hz power distribution for very long transmission distances.

The subsea VSD is the key equipment developed to control the speed and the torque of the subsea motors for seawater injection, boosting and compression applications. Here it is particularly important, that modular building blocks can be qualified and then used to configure VSD installations for a wide variety of subsea motors and loads (Figure 4). In the developed design, a single tank VSD can be scaled to run pump loads of 2 – 6 MW but also compressors requiring the 10MVA range using the appropriate number of internal cell modules and considering the maximum water temperature at the deployed location. Using a drive train with two parallel connected power conversion units, support of a load up to 18 MVA is possible. The overall solution is flexible and scalable and covers most identified needs for subsea power. The power source can be from any available topside installation or directly from shore. In case of multiple drives nearby, a switchgear will reduce the need of cables.

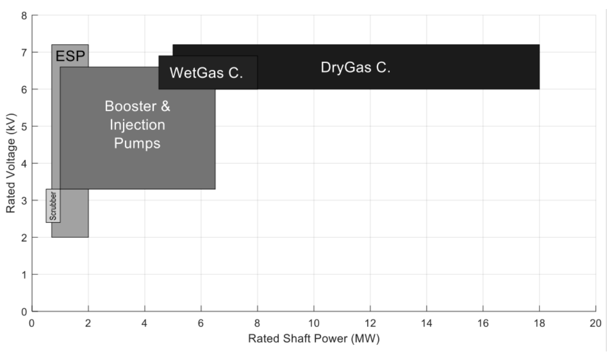

Fig. 4 Applications, power range and motor voltages typical for the subsea VSD.

Available subsea pump motors are dominantly robust induction type motors, but also permanent magnet motors exist. The subsea VSD has an integrated drive transformer which is powered via the subsea switchgear at the rated supply voltage (typically designed for a voltage in the range 11-33 kV), either at conventional 50/60 Hz or at LFAC 16 2/3 Hz supply frequency. The drive then converts the power to a variable output voltage ranging from 2.3 kV to 7.2 kV or above. The design-operating frequency range is up to 200 Hz for the full power range, up to 300 Hz for high-speed compressor loads below 5 MVA. An output filter is integrated into the VSD to ensure that the power quality and voltage transients are within motor and cable tolerances. To optimize for long service life without maintenance or repairs, the subsea VSD is based on a robust cell-based topology and long-established power semiconductors with overrating design margins. It has also built-in redundancies in both the control and power circuits. Any power cell failure is prevented from migrating to neighboring cells, whereas the faulty cell can be bypassed with the use of integrated disconnectors to continue operation. The VSD will provide full nominal power and voltage even with the loss of one cell per phase. The drive redundancy has a fault management system that is also in itself redundant at several levels. Also keeping high focus on quality, significant effort was been spent on establishing the necessary Environmental Stress Screening on a routine basis for the parts used in the drive.

Novel design solutions for packaging existing IGBT and rectifier chips were developed in order to obtain compatibility with pressure and oil environment for the subsea application. Test programs included extensive subsea-specific verifications to prove robustness of the materials adapted for the new environment. Power cycling and thermal cycling capabilities were used to demonstrate the robustness of the semiconductor modules to the load and temperature cycles in the application. Testing was generally done all the way from small components to higher assembly levels. The full power cell has separately been operated also over 3000 hours at the 345 bars qualification pressure. Part of the test were also all relevant sensors and electronic PCBAs, including the optical fibers and their connectors. The modules performed flawlessly in these pressure tests and were concluded already in 2018.

All project qualification activities followed the recommendations and technology readiness level (TRL) stages defined in DNV RP-A203, applicable for components, equipment and assemblies in hydrocarbon exploration and exploitation offshore. This recommended practice provides a systematic approach to ensure that the technology will function reliably within specified limits, and it provides a common understanding and terminology of technology status and risk management.

To ensure compact and reliable solutions, oil-filled pressure compensated tanks are used for enclosure of the VSD and switchgear. All components are tested extensively under the full pressure they will experience at the target water depth. It is a high-level objective to design the equipment to minimize production downtime and number of retrievals.

The JIP has focused on the development and qualification of a subsea switchgear, variable speed drive (VSD) and a control system. Base case is a subsea power system with a subsea switchgear feeding four VSD loads at a water depth of 3000 meter. In general, existing requirements applicable for topside systems and equipment apply, as well as API17F Standard for Subsea Production Control Systems. Equinor's technical and professional requirement TR3025 was developed in parallel with the project and specifies requirements applicable for subsea systems and equipment, e.g. system design margins and equipment immunity levels. While the JIP project over recent years developed packaging-technologies to enable robust and cost-efficient power distribution and conversion for subsea, the final goal of the project is to provide industry with the right confidence that the developed products are ready for use. This is indeed as far as ABB will take subsea technology without operational experience of the drive system in a subsea production field. Off course, before taking the steps into commercial Pilots, JIP Partners have conducted Failure mode and effects analysis at an unprecedented level of detail. This allowed identifying all relevant risks, which were subsequently mitigated by specific tests and acceptance conditions in technology qualification program. The subsea industry has adopted a TRL system (Technology Readiness Level) for a common understanding of the development stages in the qualification process, and the degree of testing required to reach each stage (see e.g. API Recommended Practice 17Q, 2nd edition). This entailed initially a breakdown of the overall subsea power system into separate manageable technology parts and classifying these in terms of novelty. The project is currently progressing from API TRL3 to TRL4 with full-scale prototypes. This includes a 4-feeder subsea switchgear, two medium-voltage subsea power drives with input transformers, and a subsea control module with the subsea protection relay. Each prototype has undergone tests at various assembly stages and have completed a final shallow waters test for 3000-hour high-power demonstration. The objective was to test and prove the thermal properties and the marinization of the equipment. Figure 5 shows the power level during the 3000 hours of operation. The power was circulated by the two VSDs through the subsea switchgear in a "power-in-the-Loop" circuit. The grid supplies thus only circuit losses. This test was structured to reflect the key aspects of field operation. One aspect of the test was a larger than 1000 h trip free phase to show the system stability. Another 6 weeks focused on severe thermal power cycling to demonstrate the highest thermal loading. In reality, this would correspond to far more than a decade of real operation, where in fact fewer full thermal cycles would be expected. These two main phases where interspersed with characterizing runs to assess the detailed thermal performance. Among other aspects, the test duration from mid-summer to early winter allowed testing over the full specified water temperature range. The final TRL assessment will be made by JIP Partner's subject experts after some remaining formal TRL 4 qualification tests on components are completed. Then the overall system will be TRL4+.

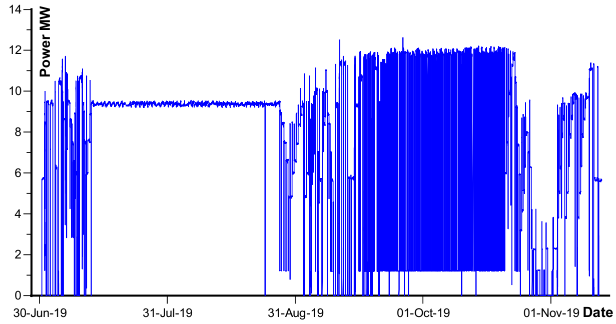

Fig. 5 Time trace of power level in VSD and switchgear during the 3000 h shallow water qualification in 2019.

Critical areas of focus for ABB, throughout the JIP, were designing the system to be modular, flexible and open and to meet reliability and availability targets that are even higher than for topside applications. The approach, from the start, has been to base the technology largely on ABB's existing technologies, where reliability is proven, where quality control and obsolescence strategies are well established and where integration with existing topside systems and software will therefore be straightforward. The design philosophy was that all failures should be mitigated by design improvement or change, rather than adding simple ruggedizing steps. Furthermore, all issues encountered during testing were shared and discussed with the project partners and sub-suppliers to draw on their field experience.

To ensure electronics and power components could tolerate operation in both a pressure tolerant environment and dielectric oil, there has been extensive focus on component screening and selection, as well as material compatibility, material interface aspects and thermal performance. The subsea electronics and control modules have been designed to be flexible and modular, allowing for variability in size, as well as positioning within the system, according to the template layout of system design philosophy. Communications and control are ethernet-based, for ease of interfacing with the rest of the subsea system, with high-speed fiber optic communications to enable responsive remote operations and an ABB Ability™-ready system.

IV. CONCLUSIONS

Having achieved qualification of all subsystems – the VSDs, switchgear and control systems – through tens of thousands of hours of exhaustive design, engineering and testing, we've now also achieved the final challenge: a full system test. All the pieces were assembled for the final 3,000-hour shallow-water test. The entire system, comprising the MV switchgear, control and low voltage distribution equipment, plus two parallel 9MVA VSDs were successfully put through its paces as a single operational unit.

The JIP results are extending the limits of what is possible subsea. The developed technology is enabling electrification of all subsea infrastructure, reducing emissions and minimizing the industry's environmental footprint; while increasing automation, process capability

V. ACKNOWLEDGEMENTS

Thanks to Chevron our JIP partner.

VI. REFERENCES

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VII. NOMENCLATURE

DEH Direct Electrical Heating
IOR
JIP Joint Industry Project
ROV Remote Operated Vehicles
VSD Variable Speed Drive.
VSI Voltage Source Inverter.
TRL Technology Readiness Level

VIII. VITA

Svein VATLAND holds an MSc in process automation from the University of South-Eastern Norway and an executive Master of Management degree from BI Norwegian Business School. Svein leads ABB's Subsea Power Joint Industry Project (JIP), bringing more than 24 years of experience in the oil, gas and utilities industries to his role. Svein has extensive management experience of knowledge organizations from several large- and medium-sized companies. He started his career in ABB in 1995 as a project engineer and has held several positions in the company, including Senior Scientist at ABB Corporate Research and Senior Project Manager, Oil & Gas. From 2009-17, Svein spent time outside ABB. Svein has authored and coauthored several technical papers.
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He joined ABB in 1994 and was active in various research and management roles in areas such as silicon and silicon carbide power semiconductor components, power electronics, Medium Voltage drives, wind energy, and electrical machines both in Switzerland and Sweden. He co-/authored more than 60 scientific publications and numerous patents. In the JIP he currently serves as Program Manager for the Subsea Power Conversion development. heinz(dot)lendenmann(at)se.abb.com

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