Controlled subsea electric power distribution with SEPDIS™

Nils Arne Sølvik, Jan Ove Gjerde, Trond Skullerud

Unlike the first generation of offshore systems, which were designed to operate on platforms located near the wellheads, second-generation systems now being installed are based on floating production, storage and offloading (FPSO), and make use of surface vessels connected to subsea wells through umbilicals. These vessels perform multiphase pumping, separation, water injection and oil storage. The next generation of production equipment will go a step further and perform all of these tasks on the seabed. This calls for an electric power supply that works reliably and economically in a subsea environment.

In the past 10 to 15 years the oil and gas industry has invested heavily in cost-effective field development solutions, with many millions of dollars spent on developing new subsea production, boosting and processing tools [1]. As an industry leader in this sector, ABB has developed new technology that can be a catalyst for the fruitful exploitation of new tools for subsea oil and gas production.

In recent years, the industry has also focused on the auxiliary systems and building blocks that will be required to establish economically sound and flexible total subsea oil and gas production systems. Within this context, the market has shown a strong interest in subsea electrical power supply systems able to transmit, distribute and control electrical power in the megawatt range. It was to meet this need that ABB embarked on the development of the Subsea Electrical Power Distribution System (SEPDIS™) 1.

SEPDIS is designed to transmit electrical power to every location requiring energy via a single subsea power cable, as opposed to the present-day use of individual cables to carry power separately to subsea consumers. Thus, SEPDIS brings to the market an electrical system solution more in line with those in use on-shore. Other advantages offered by the SEPDIS concept are greater flexibility, eg with respect to the step-out distance from the supply point, the number of consumers, step-wise system extensions, and solutions to fundamental electrical problems involving harmonics and load start-up phenomena.

SEPDIS joint industry project

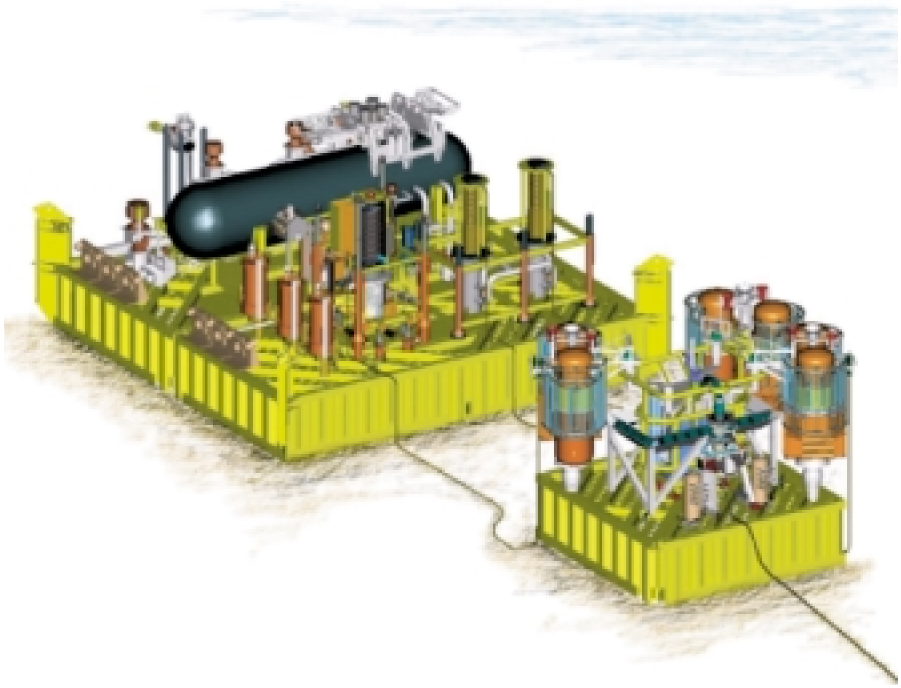
AS Norske Shell, STATOIL, Norsk Hydro ASA, Mobil Exploration Norway Inc (Exxon/Mobil), Saga Petroleum ASA (Norsk Hydro ASA), FRAMO Engineering AS, and ABB, launched the SEPDIS joint industry project at the beginning of 1997 with the goal of developing a subsea electrical power distribution system. ABB is the SEPDIS project manager and has brought together within the ABB Group the necessary expertise for the electrical components/systems and subsea mechanical engineering.

Besides providing funding, the participating oil companies have also contributed to the project with valuable technical and market inputs. This ensures that the SEPDIS development has a market-oriented focus and is designed to meet the customers' needs.

The project is divided into five phases 2:

- Concept development
- System development and design
- Prototype construction
- Prototype qualification testing
- Prototype system test

The first three phases have been completed and the results of this work now have to be verified by the qualification and system tests.



1 Overview of a SEPDIS™ installation, seen here next to the Subsea Separation and Injection System, SUBSIS (on left)

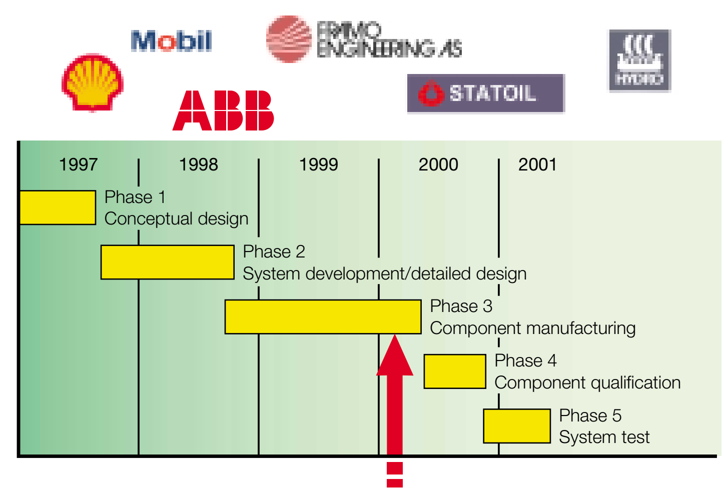
Topside electrical power supply

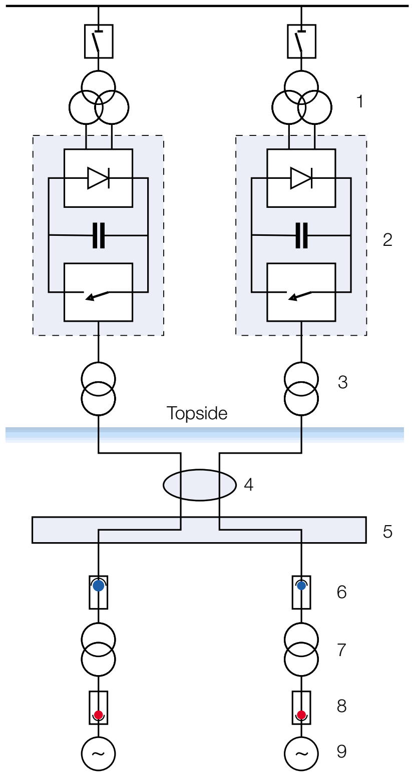
The topside electrical power supply **3** has all the appearance of a conventional variable speed drive (VSD) system, however with very long motor cables and step-up transformers. Each consumer is driven individually by a dedicated frequency converter connected via a subsea power cable.

The step-up transformers boost the output voltage of the frequency converter to a higher transmission level; in cases where the distance from the converter to the load exceeds 5 – 10 km, a subsea transformer will, however, be required.

The three-winding transformers step the grid voltage down to a level that the frequency converters can handle. They

2 SEPDIS Joint Industry Project participants and project phases.





3 Schematic of layout for a topside electrical power supply system

1 *Step-down transformer*
2 *Frequency converter*
3 *Step-up transformer*
4 *Bundled subsea power cable*
5 *Subsea cable termination*
6 *HV subsea power connector*
7 *Subsea step-down transformer*
8 *Wet-mateable pump motor connector*
9 *AC pump motor*

have three windings to permit 12-pulse rectification and thereby reduce the harmonic content fed back into the main grid.

Standard ABB frequency converters, either low-voltage IGBT or medium-voltage IGCT types, are used. They are normally rated at a substantially higher level than the load due to the long motor cables and the special load characteristics.

The step-up transformers are specially designed for operation in VSD systems, and feature high flux capacity at low frequencies. When the distances to the loads are long, a subsea transformer will be required for voltages above 6.6 kV. The motors are normally insulated for 12 kV and operate at 6.6 kV.

Special high-voltage connectors are required for the wet make/break connection between the subsea power cable and the pump motor and/or subsea transformer.

Technical design

The design of the topside electrical power system presents certain technical challenges, ranging from minimizing the size and weight of the system components to overcoming the breakaway torque of the subsea pump.

Topside drive systems with long motor cables have to be designed carefully due to resonance phenomena in the system. These occur when the harmonics generated by the frequency converter excite the resonant frequencies of the system downstream of the converter. They can be eliminated by actively controlling the converter switching frequency so that the switching frequencies that generate voltage gain > 1 are avoided. Another possibility is 'system compensation' by means of filtering, ie system impedance control.

Table: SEPDIS™ facts in brief

SEPDIS capabilities	
Total load	10 – 20 MVA
Step-out distance	0 – 100 km
Number of consumers	2 – 20
Transmission voltage	11 – 33 kV
Distribution voltage	3.3 – 12 kV
Design depth	2000 m
Installation	Guidelines
Intervention	Light vessel, modularized

The breakaway torque of the pump unit is a further design criterion. This has an impact on the flux capacity of the step-up transformer, the starting time and the current capacity of the converter.

SEPDIS

Electrically, SEPDIS is a conventional transmission and distribution system with a limited number of components and functions. Mechanically though, and in terms of its subsea capability, it is a robust and sophisticated system. The VSD sub-system topology is that of a traditional frequency converter drive system with a three-winding dedicated transformer, a 12-pulse rectifier, a DC link, an inverter and an output filter. Although the project group had decided to utilize known and proven technology wherever possible, considerable development work was nevertheless needed in some areas, including the cooling, the mechanical design, and the material compatibility and reliability.

SEPDIS was born of the idea of moving the distribution system down to the seabed to enable electrical power to be transmitted at a high voltage and the distribution system to be located close to the end-consumers. This reduces power losses, the number of subsea cables, and the space and weight requirements that have to be met by any topside facility. It also avoids on-load start-up of motors with long cables and substantially reduces problems caused by harmonics and resonance.

The transmission equipment consists of the feeder circuit-breaker and step-up transformer – both topside and of conventional design – and the subsea power cable. Typical operating voltages for the transmission system are 11 – 33 kV, depending on the total load and step-out distance. The limiting factors are the subsea wet mateable connector and the cable termination and penetrator systems, which are currently qualified for 12-kV class insulation.

The subsea main step-down transformer is the interface between the transmission and distribution systems. The distribution system is integrated in the subsea transformer module and has a simple busbar arrangement with tap-off to each load branch. Typically, the loads are subsea centrifugal pumps, driven by oil-filled induction motors. As the maximum load for such pumps is currently 3 MW, the drive equipment is dimensioned for this load. The typical operating voltage at the subsea distribution level is 3.3 to 6.6 kV (*see Table*).

Modular design

Besides the topside feeder circuit-breaker and step-up transformer, the main building blocks of SEPDIS are as shown in 4:

- High-voltage wet mateable connector (MECON [2]), cable termination and penetrator system
- Subsea step-down transformer and distribution system
- Distribution-level wet mateable connectors
- Subsea frequency converter modules, including protection circuit-breaker and control system interface
- SEPDIS control system
- Base frame, installation and intervention equipment and tools

Main support structure/ base frame

The frame 5 is based on the ABB Modular Subsea System Production template. This flexible system with hinged guidepost receptacles can also be installed through a moonpool (the installation pit offering direct access to the sea from the deck of a ship or drilling rig). Some modifications have been made to the base structure system to accommodate SEPDIS.

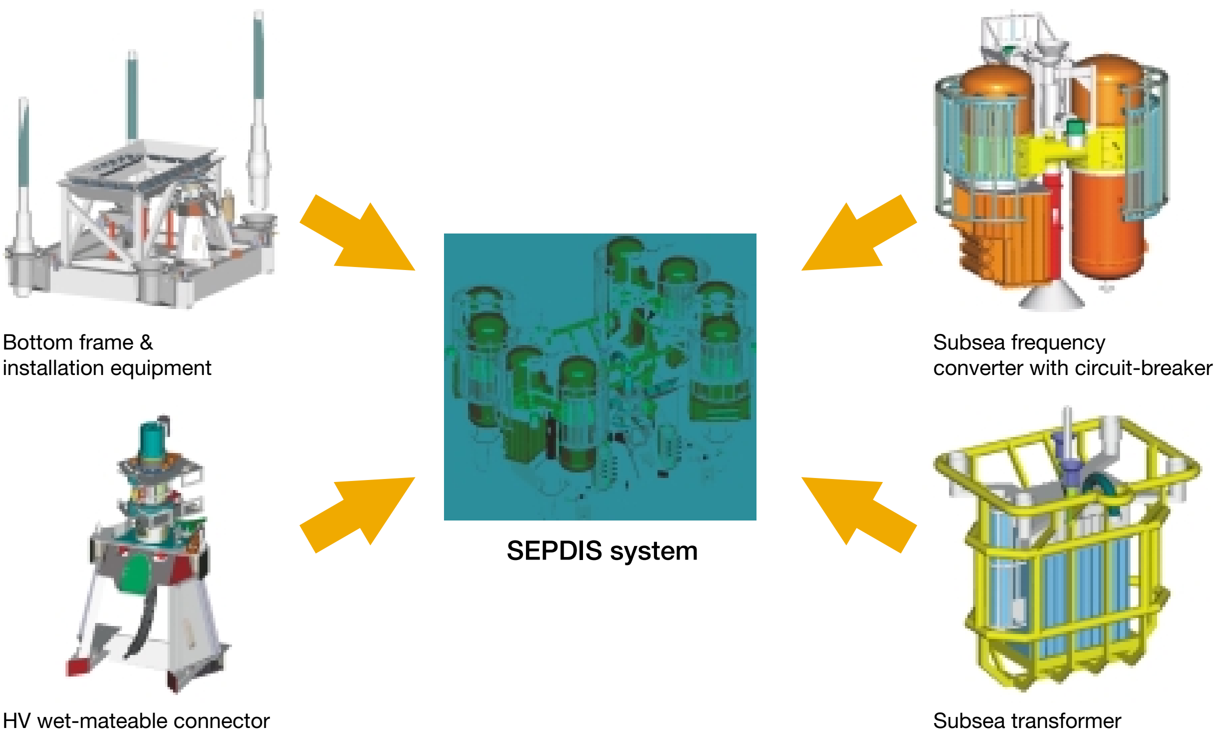
Three different types of foundation are available for the base frame: a skirt, a suction anchor, and a mono-pile. The main function of the foundation structure is to provide support for the steel frame during installation and operation.

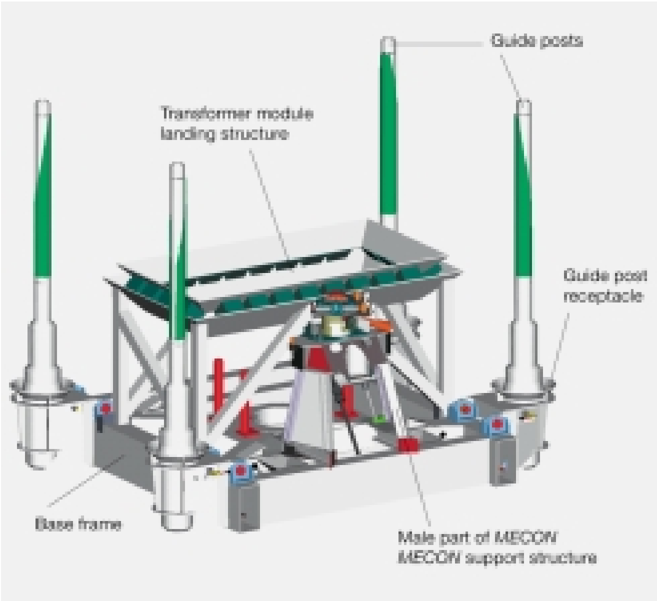
The steel framework measures 6 x 5.5 m (for a 4-slot template) and has a circular interface for attachment to a suction anchor or a mono-pile seabed support, centered on the frame.

A rectangular guiding structure in the center of the framework is for the transformer module. Guideposts welded into the corners of the box ensure proper elevation and horizontal positioning of the transformer module, thereby making sure that the connection points between the transformer and the power supply modules are properly aligned.

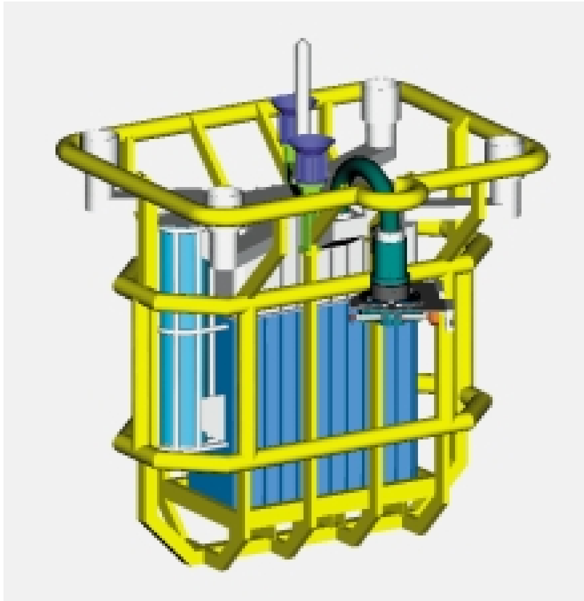
Each base frame assembly can have up to five guidepost receptacles. Their function is to provide a guiding and landing interface for the guideposts during installation and to support the weight of the guidepost and power supply unit during operation.

4 The main building blocks of SEPDIS





5 Mechanical layout of a base frame with four guide posts



6 Subsea power transformer module

The guideposts, which are shaped like steel rods, also ensure that the frequency converter module, direct on-line motor starter and auxiliary power modules, etc, are properly aligned and supported.

Subsea transformer module

The main parts of the subsea transformer module 6 are:

- Main subsea transformer
- Expansion tank
- High voltage penetrator (upper male part of MECON DS connector)
- Subsea distribution level penetrators (lower male parts of MECON NM connectors)
- Protection structure
- Guides and funnels for installation/ retrieval

The transformer core and windings and the integrated distribution busbar arrangement are placed inside an oil-filled steel tank. Tank volume compensation is provided by internal and external systems. Cooling is by natural convection via the water to the surroundings.

Connection to the power transmission cable is by means of a MECON connector, one male part of which is already fitted to the transformer module (HV transformer feeder). Subsea distribution-level wet mateable connectors are used between the distribution level (transformer) and the consumer branches. Besides the power transmission system, there is a control system for monitoring the temperature and pressure inside the module. This system communicates with the subsea distribution unit via control jumper cables and standard ROV (Remotely Operated Vehicle) operational wet mateable control connectors.

Subsea frequency converter module

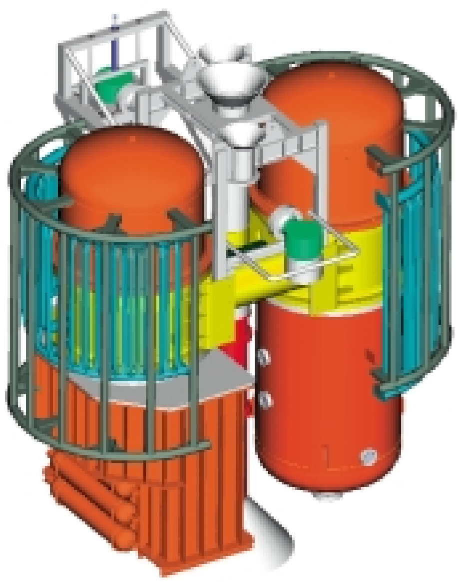
The subsea frequency converter (SubseaFC) module is connected to the main subsea transformer by connectors and jumper cables.

The SubseaFC module 7 comprises the following sub-systems:

- Subsea distribution-level connectors and penetrators
- Protection circuit-breaker
- Three-winding transformer
- Frequency converter
- Cooling system
- Pressure vessel
- Control system
- Soft-landing system, guides, lock down and running tools

The three-winding transformer is situated in a pressure-compensated, oil-filled tank. The oil acts both as an insulating and cooling medium. A 1-bar pressure vessel encapsulates the rest of the module, including the power electronics, capacitors, etc. The converter cooling system is passive, so that neither fans nor pumps are needed.

The module's overall control and monitoring system, including integrated motor protection functions, is based on standard technology. Designed for high reliability, it has its own, separate power supply to enable it to be energized before the high-power circuitry.



7 Subsea frequency converter with pressure vessel

SEPDIS – technical challenges

A project as ambitious as SEPDIS presents a whole series of technical challenges: a subsea electrical power system has to ensure high reliability and availability and at the same time have the robustness and compactness needed to keep installation and intervention costs down. Technical challenges in the electrical area involve harmonics and overvoltages as well as the increased stresses caused by reflections in the power cables. In the mechanical area, the cooling and encapsulation pose special problems.

Topside transformer

The rating of the delta-star connected transformer is determined by the bulk power required by the subsea consumers. Tap changers are provided to compensate for voltage variation caused by fluctuations in power consumption, especially during direct start-up of the large induction motors.

The neutral point (on the secondary side) is grounded via a Peterson coil to reduce the voltage stresses that could be caused by a single-phase earth fault on the power cable.

Power cable

High-voltage (11-33 kV) power transmission has advantages in the cable dimension, cost, voltage drop and power loss areas.

The length of the power cable depends on the distance between the topside installation and the consumers, including the water depth. This length is a crucial factor since it has an effect on the reflections, oscillations and overvoltages.

Subsea distribution transformer

At the end of the power cable there is a step-down transformer connected in delta-star which lowers the voltage to an appropriate subsea distribution level (SDL). The transformer rating is determined by the power requirements of the consumers. The distribution transformer is grounded at the SDL level via a resistance to ensure a detectable fault current at minimum load.

High-voltage motors

With SEPDIS, large induction motors can be connected directly to the subsea distribution system. During direct on-line starting of these motors, the reactive current taken from the network can be four to six times the nominal load current at the rated motor voltage.

A problem here is that reactive power support, while necessary to start the induction motors, can also adversely affect other consumers connected to the system (the voltage may be too low).

Additional LV consumers

If required, additional low-voltage consumers can be connected to the SDL system via a transformer. It is assumed that these consumers will be able to operate normally within the SEPDIS system even when there are large voltage deviations.

Subsea frequency converter

Power electronics devices, such as rectifiers and converters, are commonly encountered sources of harmonics. They produce harmonic currents in the electric system, injecting them at the point where they are installed. Any number of harmonic current sources may be present in the system, and each source will spread according to the impedance met at its frequency.

With SEPDIS, a number of drive systems can be connected to the common distribution busbar.

The harmonic content of the voltage largely determines the power quality as the network components are built to operate at the power frequency, ie 50 or 60 Hz, and harmonics normally lead to additional heating and electrical stresses in components connected to the power system. Harmonics arise in the systems due to loads having non-linear characteristics. The characteristics of each drive system can be identified by analysis or measurement.

The 3-MVA SubseaFC is a key component of SEPDIS. Based on the newly developed ABB ACS 1000 converter concept [3], it allows individual control of the connected motors with respect to torque, active power and speed.

ACS 1000 series converters are available in the voltage range of 2.3 to 4.16 kV and a power range of 0.4 to 5.95 MVA. These converters combine improved performance and high reliability with a small footprint and low height.

The SEPDIS design for deep waters features a very thick pressure vessel, thus limiting heat transfer through the walls. As already mentioned, a passive cooling system, without fans and pumps, is used to increase reliability. This is a heat cycle system in which the heat-generating components are placed in a cooling liquid with a relatively low boiling point; the vapor passes to the outside of the tank, where the seawater cools and condenses it before it returns to the pressure vessel.

Extensive changes to the existing product design are necessary due to the special requirements of a subsea environment.

As the variable speed drives produce voltage and current harmonics, frequency domain analysis is used to characterize the power system's behavior and identify critical frequencies that the drive systems should not produce, thereby lowering the risk of damage to the system components.

It is also necessary to investigate the frequency response of the power system before selecting the converter modulation technique. Detailed modeling of each system component is required, which should include a distributed parameter model for the power cable.

Outlook

The Subsea Separation and Injection System (SUBSIS) [1] and SEPDIS together mark the onset of a new era in oil and gas production, and will also mark the beginning of the end for many large offshore platforms and floats.

The demand for electrical power for subsea consumers will increase with the new processing solutions. ABB is working on new AC and DC power system solutions that will enable the offshore industry to meet the new requirements brought about by increased power levels, step-out distances and depths.

Based on the SEPDIS concept, a feasible technical solution has been identified for long distances (150 km) with a maximum power level of about 40 MW. This solution, which could be used for a power supply from the shore or from an existing remote infrastructure, will be evaluated through the current SEPDIS project. Additional qualification and tests are needed for the high-voltage connectors and penetrators (voltage level $>$ 36 kV).

Authors

Nils Arne Sølvik
ABB Offshore Systems AS
NO-1361 Billingstad
Norway
nils.solvik@no.abb.com
Telefax: +47 668 445 45

Jan Ove Gjerde
Trond Skullerud
ABB Corporate Research AS
NO-1361 Billingstad
Norway
jan.o.gjerde@no.abb.com
trond.skullerud@no.abb.com
Telefax: +47 668 445 88

References

[1] **R. Strømquist**, **S. Gustafson**: SUBSIS – world's first subsea separation and injection system. ABB Review 6/98, 4-13.
[2] **I. Østergaard**, **G. Sande**, **A. Nysveen**, **F. Greuter**: MECON – a novel high-voltage subsea power connector. ABB Review 3/99, 37-42.
[3] **S. Malik**, **D. Kluge**: ACS 1000 – world's first standard AC drive for medium-voltage applications. ABB Review 2/98, 4-11.
[4] Converter fed sub sea motor drives. **Rolf Ove Råd**. PhD Thesis, Norwegian Institute of Technology, 1995.