Abstract

Subsea tiebacks are becoming increasingly prevalent in oil and gas field developments. As the accessibility of the production from wellheads becomes more difficult, the need for subsea compression and pumping increases. Compression and pumping require significant power which can be distributed and controlled from a HVSS (High-Voltage Subsea Substation). The viability of an Arctic field development will be determined by the reliability of all elements in the tieback and in particular, the centralized subsea power distribution system.

Introduction

This paper presents the conceptual design and capabilities of a modular, expandable and highly reliable subsea HV (High Voltage, U > 1000 V) and LV (Low Voltage, U ≤ 1000 V) power distribution system. The assembly is designed to operate without intervention for extended periods of time and is ideally suited to emerging green field developments in the Arctic. The concept is built from components and subsystems each with a technology readiness level of six or seven and is therefore well positioned for a prototype build and deployment with minimal additional qualification.

The core switchgear is built around proven 36 kV CBs (Circuit-Breakers) connected together via an SF$_6$-insulated bus bar. The use of SF$_6$ as a dielectric medium allows the size of the CBs and bus bar pressure vessel to be minimized, reducing the mass and thus deployment constraints of the assembly. Connections to the switchgear assembly for both the incoming power feed and switched outputs are via wet mate connectors. The only components in the main pressure vessel are the CBs, current transformers, voltage transformers and busbars.

To maximize the overall system availability, the control and protection systems for each 36 kV CB are redundant and housed in a series of recoverable modules rather than inside the main HV switchgear pressure vessel. Should there be a fault in the control and protection system, the redundancy is designed such that a faulty module can be replaced without loss of control of its associated 36 kV CB, thus maintaining production availability.

A key and unique feature of this switchgear assembly design is the ability to power all of the protection, control and communication equipment independent of the main HV AC power. This is achieved by including two high voltage direct current and fiber optic cables in the umbilical. At the switchgear module, the HV DC voltage is stepped down to LV DC via a pair of redundant nodes that distribute auxiliary power and communication capabilities to the subsea equipment. By independently powering the control and monitoring system, the status and position of each CB can be known during a black start without the need for a subsea battery-supplied UPS (Uninterruptible Power System). In keeping with the simple and robust design philosophy, only critical telemetry is provided to monitor and control the system. Where telemetry is provided, it is also redundant.

This paper will describe in detail the key design features of the subsea power distribution system. These have been selected in order to achieve a highly reliable system with a predicted availability of > 99% for five years based on a mean maintenance access window in the Arctic environment of six months.

Single-Line Diagram

Fig. 1 shows how power is supplied to the subsea process loads. Power comes from a shore station which could be on an offshore platform or on land. A power umbilical comprising the HV AC cables as well as fiber optic cables for communication and HV DC cables for auxiliary power connects the shore station to the subsea power distribution system which is shown below the dot-dashed line. The voltage used for the HV AC cables will depend on the step-out distance and could be in the...
110 kV range. The voltage for the HV DC auxiliary power typically ranges between 2 kV and 10 kV depending on the step out distance and power requirements.

The power umbilical consists of several cables within the same assembly. Each cable is connected to different equipment both at the shore station and subsea. At the shore station the cables are collected together at the TUTA (Topside Umbilical Termination Assembly) into the umbilical and split apart subsea at the SUTA (Subsea Umbilical Termination Assembly). From the SUTA each cable is terminated at different equipment. The part of the single-line diagram downstream from the umbilical connection to the SUTA is shown in Fig. 1.

**HV Power Circuits**

HV feeders will power the process loads. The main loads shown in Fig. 1 are pumps and/or compressors. The power output of each process load is controlled by means of a VFD (Variable Frequency Drive). The step-down XFMR (transformer) associated with each VFD converts the distribution voltage (22 kV to 33 kV) to a value that can be directly fed into the VFD (6.6 kV for example). The auxiliary transformer shown within the VFD is used to precharge the capacitors of the VFD DC circuit to prevent unacceptable inrush currents when the VFD is energized. It also premagnetizes the VFD step-down transformer, which limits the magnitude of its inrush current.

**LV Power Circuits**

LV power is required for many subsea loads. These include valves, AMB (Active Magnetic Bearing) power amplifiers and controller, communication systems, process control and many others. Most LV power is required when the process is in operation and thus can be supplied via the HV AC power system by means of an HV/LV step-down transformer shown in Fig. 1. An example of this is the VFD capacitor charging supply. The only time this circuit is energized is just prior to switching on the VFD. Switching on the VFD will occur when HV AC power is available.

Some loads require secure power. One of the most important loads is the auxiliary power required for the communication system. Without communication the shore-station operators no longer know the status of the subsea power distribution system or the process loads. Remote control to place the equipment in a safe mode is also not possible without auxiliary
power. The same applies to the power amplifiers and controller of the compressor AMB. Should the HV AC power be lost for any reason, the normal power supply to the AMB will be lost and damage can occur during the time the compressor slows down and stops. During this time it is necessary to provide power from an independent source to keep the magnetic bearings energized until such time as the compressor has stopped.

Secure power can be provided in different ways. One possibility is the use of an AC UPS powered by the HV AC supply and having its own backup battery. The main disadvantage of this solution is the difficulty in sizing the battery. Auxiliary power must be available to check the status of the HV CBs and other equipment prior to energization of the HV AC cable in the umbilical. Since the HV AC power outage could be of long duration if a major event happened, the battery could discharge before reenergization is attempted. It would probably be necessary to have charged batteries available that could be deployed to energize the auxiliary systems to provide safe black-start conditions. This could cause a substantial delay in reenergization.

Another possibility is the use of an HV DC power supply via dedicated conductors within the umbilical. If this supply is powered by a battery-backed UPS on the shore station, then it is most likely that an additional source of backup power (subsea batteries) will not be required. The HV DC supply will provide the power required during compressor shutdown even when there is a loss of the HV AC supply. Since the HV DC supply provides auxiliary power to the communication, monitoring and control systems, these can be energized before the HV AC cable without the need for a subsea battery. Thus safe start conditions can be achieved without having to use vessels, even after a very prolonged outage. This solution is shown in Fig. 1.

Enhancing Availability
Availability is defined as MTTF / (MTTF + MTTR), where MTTF is the Mean Time To Fail and MTTR is the Mean Time To Repair. To enhance availability it is necessary to increase the MTTF and decrease the MTTR. Decreasing the MTTR for subsea installations is difficult due to the requirements for ships, relatively good weather, and perhaps absence of ice cover. The method used in the design presented in this paper is to house all electronic equipment is specific enclosures that can be individually retrieved. These enclosures are small and have a mass of approximately 1000 kg. Even though an ROV (Remotely Operated Vehicle) using a buoyancy device could retrieve a module under ice cover, it would still take several days or weeks to do so. Thus trying to improve the availability by only reducing the MTTR is not enough.

Increasing the MTTF is also required. In many ways subsea installations resemble inter-planetary space missions for which increasing the MTTF is the only alternative since maintenance is impossible. One method used to increase the MTTF is to build fault tolerance into the design. Here it is necessary to be very careful since fault tolerant designs often require some additional equipment. More equipment means more chances of failure, more complexity in the design and more possibilities to get things wrong. Using existing equipment to provide fault tolerance for other equipment as described later, is one way of increasing the MTTF without adding components.

The remarks above imply that the equipment has been correctly designed prior to manufacturing. Even though the supply of equipment may be split among different vendors, a complete electrical system design from the shore-station to the loads must be performed. This system design will define the characteristics of all electrical equipment and must consider harmonic currents from VFDs, the tens of Mvar of reactive power generated by subsea cables, load variation, switching surges, inrush currents etc. The list is long but must be done prior to ordering any equipment.

High-Voltage Subsea Substation (HVSS)
The HVSS consists of several parts as shown in Fig. 1. These are the HV CBM (Circuit-Breaker Module), HV BCPS (Breaker Control and Protection System), HV/LV step-down transformer, LV SD (Subsea power Distribution) and UPS. The umbilical, SUTA and the main HV/HV step-down transformer (if required) are not described in this paper but form an essential part of any subsea power distribution system. There are some major installation considerations regarding the connection between the SUTA and the main HV/HV step-down transformer. This is due to the fact that wet-mate connectors for voltages above 36 kV are not yet available and thus such connections must be made topside prior to installation.

Although not specifically described in this paper, all subsea cables for interconnection of the parts of the HVSS and connection of the loads are a very important part of the subsea power distribution system. These cables are often very rigid and have a large bending radius which must be taken into account in the design of all equipment.

All HVSS equipment will be installed on subsea templates. The fixing of these templates to the seabed can be very complicated. Generally the subsea template and related civil works structures are provided by third parties.

HV CB Module
The CBM shown in Fig. 2 uses GIS (Gas Insulated Switchgear) technology that has been proven over the last few decades in terrestrial systems. The HV power circuits consist of CBs, CTs (Current Transformers) and VTs (Voltage Transformers) and a common busbar. All these devices are installed within pressure vessels filled with SF₆ gas. Each CB and related CTs are installed within a separate SF₆ filled vessel to facilitate fabrication of the CBM. Each CB enclosure is connected to the SF₆-filled busbar enclosure resulting in the very compact subsea 36 kV CBM.

In the lower left corner of Fig. 2 the cables shown penetrating each cylindrical vessel are connected to the CB control mechanism and the CTs of each HV circuit enclosed within. The other end of these cables is connected to the stab plates of
the backbone shown in Fig. 2 and described below. The backbone is installed on the CBM and provides the interface between the BCPS and the power components of the CBM.

**Breaker Control and Protection System (BCPS)**

The switchgear requires protection relays to disconnect faulty equipment, as well as to monitor and remotely control operational equipment. All of these require auxiliary power as does the CB itself with its spring-charging mechanism, and its close and trip coils. Since the HV CB module only contains HV power devices, separate enclosures are provided for these other functions. In order to provide a compact design, these enclosures are located above the CBM structure and connected to the power equipment via the backbone stab plates which are shown in Fig. 2. The complete BCPS is shown in Fig. 3 and consists of 4 different types of modules.

The first type of module is the node. The node converts the HV DC power to LV DC which can be used to power the protection relays, CB spring charging mechanisms, close and trip coils and the communication, monitoring and remote control system equipment. The node also houses the communication hubs connecting all subsea equipment to the monitoring and control systems located at the shore station. There are two 100% redundant nodes meaning that the process can continue during the time required to replace a faulty node.

The second type of module is the BCPM (Breaker Control & Protection Module). One BCPM is provided for each HV CB. Each of these modules is connected to both nodes and to two CBs. Fault tolerance has been provided by designing the BCPM such that each controls two CBs. Thus failure of one BCPM will not require a process shutdown since the adjacent BCPM can provide the protection and control of the HV CB during the time required to replace the faulty BCPM. This is an example of providing redundancy without increasing the amount of equipment needed.

The third type of module is the backbone which is shown in Fig. 2. The backbone stab plates provide the means for connecting the nodes and BCPMs to the CBM. The stab plates allow the ROV to make and break all cable connections to a node or BCPM at one time by means of a torque tool.

The Input Module shown in the bottom left corner of Fig. 3 is the fourth type of module. It provides the connection of the HV DC and fiber optic cables from the SUTA to the backbone via stab plates and thus to the nodes and BCPMs. An Expansion Module can be installed above the Input Module. This allows an additional HVSS to be connected downstream using the same HV DC and fiber optic cables in the umbilical. The Input and Expansion modules are mounted on an individual support that will be lowered onto the subsea template for connection to the rest of the HVSS.
LV Subsea Power Distribution (LVSD)

The HV/LV step-down transformer is installed within a pressure compensated double-walled vessel. The transformer has a fixed turns ratio and the core is sized to allow for long-term over-voltage conditions. The transformer enclosure is designed such that possible marine sediment will not degrade the thermal dissipation of the vessel to sea water over time. Transformer accessories are connected via the LV SD. The condition of the transformer is thus made available to the shore station operators. Tripping of the HV CB supplying the transformer is done via GOOSE\(^1\) messages.

The LV switchgear is contained in a pressure vessel filled with dry nitrogen at one atmosphere pressure. Standard LV CBs and other devices are used. All CBs are motor operated to allow remote switching and resetting after tripping due to overload conditions. Each CB has a communication interface for monitoring and remote control. This communication interface also allows remote setting of the overload protection. This is very important since precise information regarding the characteristics of the loads may not be available at the time of installation thus requiring protection setting modifications after installation on the sea bed.

The communication interface is designed to be fault tolerant in the same manner as for the HVSS described above. Standard communication interfaces are used which enhance the availability of the complete system. Auxiliary power for the communication equipment and CB operation can be derived from the upstream terminals of the incoming CBs or obtained from the nodes of the BCPS. Communication will be via fiber optic cables connected to the nodes of the BCPS.

The LV power distribution has an isolated neutral allowing operation with a single earth fault. As shown in Fig. 4, each outgoing feeder has an isolation transformer thus making the LV distribution system immune to earth faults in the loads themselves or in the connections to them.

For some applications redundant LV switchgear may be required. In such cases dual step-down transformers would also be required and there would typically be a cross connection between both LV SDs. Control and auxiliary power systems would also be cross coupled.

\(^1\) Generic Object Oriented Substation Event (GOOSE) messages are defined in the IEC 61850 set of standards. These messages are typically used for tripping and interlocking and are transmitted via the communication system. Hard-wired connections are not required.
Monitoring and Remote Control
Communication is provided for all devices installed subsea. Using Ethernet technology and fiber optic cables installed within the subsea enclosures and power umbilical, information regarding the status of each device can be obtained allowing operators to determine appropriate control actions. Since this equipment is powered independently of the HV AC power, the status of the HVSS can be known and modified prior to energizing the HV AC cable in the umbilical. This black-start requirement is essential for all subsea power distribution systems.

Interlocking is provided in the shore-station control equipment and not in hardware installed subsea. In a crisis situation authorized operators can execute orders that normally would not be allowed, or inhibit protection functions. This could result in equipment damage but that will be a judgment call based on the particular circumstances. Such actions would normally require upper management approval.

Equipment such as the HV/LV step-down transformer and the LV SD need to be connected to the communication system in order to be integrated into the monitoring and remote control system. Also in some cases access to the DC power may be required. Both the communication and DC power are available in the nodes of the BPCS. To allow connection to both, an ROV panel is provided on the BCPS to which fiber optic and DC power cables can be connected. The ROV panel is connected to both nodes via the BCPS backbone allowing access to both nodes and the redundant Ethernet switches and DC power supplies in each. Although initially intended for use with subsea distribution equipment, this ROV panel could also be used to provide a communication link and DC power for third party subsea equipment.

Testing
Comprehensive factory testing is of utmost importance for subsea equipment. Once installed on the seabed, adjustments and repairs are no longer possible. All electronic devices should be subjected to burn in to eliminate those that would fail due to the initial, high-failure rate portion of the bathtub curve of component reliability. It is not enough just to verify the correct operation of all components and all equipment and systems. Incorrect operation that could be detrimental to the equipment or production must also be avoided. This is much more difficult to verify since there is an unlimited number of combinations of conditions that could lead to malfunctions. Situations such as "Everything tripped and we can't reenergize" must be avoided.

System testing should be extensive. This will mean assembling all parts of the subsea power distribution system at the same location, connecting all equipment and performing functional tests. This type of testing is expensive and takes time but due to the nature of subsea installations it is considered by the authors as a fundamental requirement. All interfaces with third party equipment must also be tested at this time.

It is also necessary to have very detailed test procedures to avoid producing situations that could lead to failures after final installation. Every tool and accessory used for each test should be documented and checked before the test is carried out and afterwards. This will avoid accidentally leaving something within a vessel that could cause a failure afterwards (the equivalent of the surgeon's glove sewn up in a patient).
Modularity - a Requirement for Installation and Retrieval

In order to be able to install a subsea processing facility consisting of equipment shown in Fig. 1, it is necessary to be able to separate the complete system into several modules. This requires means to connect and disconnect cables subsea. Although this technology has been available for LV and fiber optic cables for some time, only recently has it been possible to do the same for HV cables.

HV Power Connections to Supply and Loads

Subsea connection and disconnection of HV circuits requires two key technological items, a penetrator which connects a subsea cable to a CB within a vessel, and wet-mate connectors that allow circuit connections. Both of these items are shown in Fig. 2. The penetrators are shown on the top of each CB vessel and are connected to short lengths of cable via 90° elbows. Specially designed clamps hold the cable during all installation conditions, from atmospheric pressure during fabrication to several hundred bars on the sea bed. In order to avoid small bending radii, the wet-mate connectors for each cable are physically located above the CB vessel on the opposite side as shown in Fig. 2.

Connected to the other end of these short lengths of cable are the wet-mate connectors. These allow loads and the incoming supply (supplies) to be connected and disconnected subsea. These are ganged single-core connections.

The other part of the wet-mate connectors are mounted on separate cable supports as shown in Fig. 5. Specific landing areas for these supports are provided on the subsea template. The template provides the coarse alignment of the male and female wet mate connectors, and fine adjustment is provided on the connectors themselves. The subsea cables connected to the wet-mate connectors can be directly connected to the loads. Thus the complete subsea assembly consisting of the load, its cable and the cable support can be installed and removed as one unit.

The right-hand image in Fig. 5 shows the cable support with its wet-mate connector in the disconnected position. To the left of this image the complete wet-mate connector system in the connected position is shown. The operations of connection and disconnection are done by the ROV.

Installation

All equipment installed subsea will be shipped to the location and lowered to a subsea template. The design of the equipment must take this into account. Not considering the power umbilical, the largest single piece of equipment in the subsea power distribution system described in this paper is the HV circuit-breaker module. Without the cable supports, its footprint is a 6 m square, its height is 5 m and its mass is approximately 80 000 kg for 2 000 m depth. It would fit through a moon pool of a larger ship. The HV power cable supports shown in Fig. 5 will first be connected to the subsea cables or flying leads together with the loads, and then separately lowered and fixed to the template. Afterwards the electrical connection can be made with the ROV.

In most cases all BCPMs and nodes will be installed on the CBM and connected to the backbone on the surface and the complete CBM / BCPS assembly will be lowered to the subsea template. Should the weight of the equipment be an issue, the CBM could be lowered without the nodes and BCPMs installed, reducing the mass by approximately 8 000 kg. The nodes and BCPMs would then be individually installed subsea and connected by the ROV.

Retrieval

Fig. 6 shows the retrieval of a BCPM. After disconnecting the stab plate and thus releasing the BCPM, either a cable is connected to the BCPM as shown in the Fig. 6 or a buoyancy device is attached. The ROV is shown guiding the BCPM being removed. This is to prevent damage to surrounding equipment. The same retrieval procedures apply to the nodes.
Ease of installation and retrieval are also demonstrated by the design of the cable support interface shown in Fig. 6. Each cable connection support can also be individually retrieved together with the cable connected to them and perhaps the load if it is connected directly to the other end of the subsea flying lead. This would require the use of a topside crane.

Fig. 6 Breaker Control and Protection Module (BCPM) Retrieval

Conclusions
Rethinking the traditional design process is required for the design, manufacturing, assembly and testing of a subsea electrical distribution system. The most significant design criterion is the difficulty of human access for maintenance or operation at the equipment location. Keeping in mind some general principles such as “leave nothing to chance” and “what you don’t fit costs nothing and needs no maintenance” will help when making decisions.

References