ENERGIZATION OF SUBSEA POWER TRANSFORMERS

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Abstract –Energizing large transformers often cannot be done direct-on-line due to the negative effects of the inrush current. The typical schemes used in the past are energization via a high impedance, or via a tertiary winding connected to an auxiliary AC power source. These schemes require additional equipment resulting in increased foot print and complexity. For offshore and subsea installations, the increase in foot print often greatly exceeds the cost of the additional equipment.

This paper presents an alternative solution allowing direct-on-line energization of large transformers, both topsides and subsea. Different solutions for subsea auxiliary AC power supplies not requiring high-voltage circuit-breakers are presented.

For offshore and subsea power systems, the circuit-breakers supplying power to the transformers are standard 3.3 kV to 36 kV class devices having a 3-pole operating mechanism. The solution presented allows circuit-breakers to be switched such that the closing of the poles occurs at the point on the voltage waveform where the resulting inrush current is the least. For subsea power distribution systems, the auxiliary power required for the subsea control equipment is provided by a high-voltage DC auxiliary power link from the shore station and the control and communication link is via optical fiber.

The solutions presented use standard proven technology and can be integrated within the subsea modules required for supplying power to the loads. This keeps the number of penetrators and subsea connector systems to a minimum. The importance of redundancy and maintenance in obtaining and keeping the required system availability are discussed.

Index Terms — Transformers, Inrush Current, Subsea and Offshore Installations, Adjustable Speed Drives

I. INTRODUCTION

Fig. 1 shows a generic one-line diagram for supplying power to subsea processing loads. The link to the topsides facility is by means of a power umbilical shown connected to both the topsides umbilical termination assembly (UTA) and its subsea counterpart, the subsea umbilical termination assembly (SUTA). The umbilical consists of the main AC power cable supplying energy to the subsea loads, the optical fiber cable for communication, and DC auxiliary cables to power the subsea control equipment.

The one-line diagram shows the use of subsea switchgear and subsea adjustable speed drives (ASD). The common alternative to this system in which the switchgear and ASDs are located topsides will be discussed later.

There are several technical issues that must be solved when designing a subsea power distribution system as shown in Fig. 1. These are:

- Determining the status of the subsea power equipment prior to energizing the power umbilical (black-start function)
- Providing low-voltage auxiliary power for subsea loads
- Avoiding system disturbances when energizing power transformers
- Avoiding damage to ASD capacitors due to sudden energization

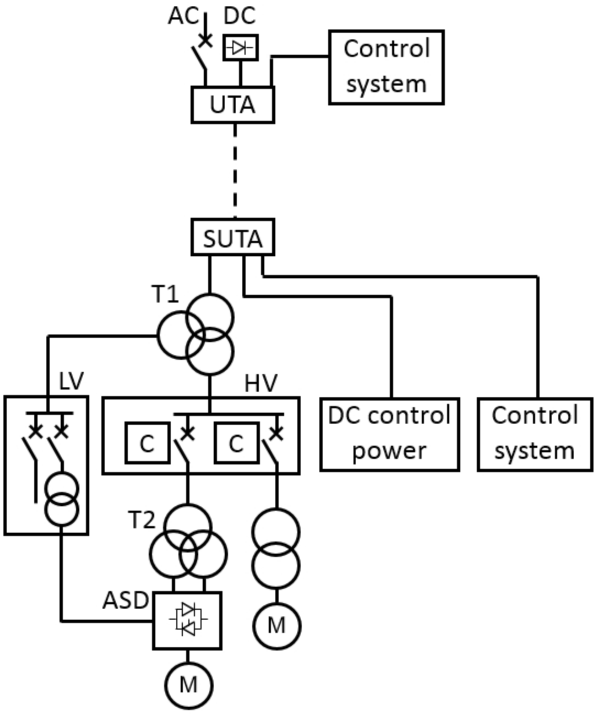

Fig. 1 Subsea Processing Power System

In the diagram shown in Fig. 1, the main loads would be subsea compressors, or subsea booster/multiphase pumps having rated power in the 1 MW to 15 MW range. The voltage used in the power umbilical will depend on the step-out distance and the subsea loads, and could be up to 110 kV. The subsea switchgear is typically operated at 20 or 30 kV. The compressor and/or pumps are powered via ASDs which are supplied by step-down convertor transformers. The other high-voltage HV motor (HV > 1000 V) in Fig. 1 is a water injection pump that is operated in an on/off manner. Some small subsea low-voltage loads (LV ≤ 1000 V) also require power. These LV loads may or may not require power prior to the energization of the main HV power circuit. One auxiliary load for subsea compression that requires special care is the magnetic bearings. This load must also be powered during emergency shut-down conditions when all power is lost.

Fig. 1 shows the use of a tertiary winding on the main step-down transformer to provide LV auxiliary power subsea. This auxiliary power is present only after energization of the main power circuit to the subsea installation and thus cannot be used for the black-start function. After energization of the main power circuit, LV auxiliary power is available for all LV loads not required for the black-start function. The use of a tertiary winding avoids installing a separate HV-LV subsea transformer and additional HV circuit-breaker (CB). Alternative methods for providing LV auxiliary power are presented later in the paper.

The HV CB control devices are indicated by the letter C in Fig. 1. The purpose of these control devices is to close the HV CBs at a time that minimizes the transformer inrush current. They are integrated into the overall control and protection scheme of the complete power system.

II. LIMITING INRUSH CURRENT

Power transformer inrush current has many negative effects in power systems including:

- Rapid voltage changes (voltage dips) that may oppose the grid code requirements defined for the interconnection with the landline power grid. In many countries, the voltage dip cannot be higher than 3%, imposing the necessity to integrate inrush current mitigation [1].
- Voltage transients and surges on cables that may exceed their operational limits as well as those of the interconnected electrical equipment
- Mechanical and electrical stress in the transformer and the CB can reduce the service life of the equipment and thus could require additional maintenance.
- It may be necessary to desensitize the protection relay in order to allow transformer energization without tripping. This reduces the reliability of the protection scheme.

Power transformer inrush current is mainly due to the presence of residual flux in the transformer core resulting from its previous de-energization. The magnitude and the polarity of the residual flux depend mainly on the transformer load and the de-energization moment relative to the voltage waveform.

A. Inrush Current Mitigation

Transformer inrush current can be mitigated using conventional techniques with series impedance (pre-insertion resistor, smoothing reactance) or by powering the transformer at reduced voltage. While it is possible to implement these solutions in onshore facilities, the cost due to the increase in footprint for offshore installations is prohibitive. Such solutions are not practical in subsea installations due to the additional requirements of minimizing the component count and connections.

The best option to mitigate the transformer energization inrush current is to use a controlled switching device (CSD). This technology has been used successfully for years with HV power transformers and offers the best possible mitigation of inrush current. This solution can be integrated into the subsea processing power system shown in Fig. 1.

In power transmission applications, the CSD mitigation technique has been initially used with CBs having independent pole operation or staggered pole mechanism. However, these devices are not common in HV applications with rated voltages ≤ 36 kV used in subsea systems. For such systems, the use of 3-phase CBs with simultaneous pole operation is a requirement.

For any residual flux pattern in the transformer core, there is always an optimum energization moment that results in minimum inrush current. This principle is illustrated in Fig. 2, where the inrush current is shown for each phase relative to the CB closing angle deviation from the ideal energization instant. For this given flux pattern, the inrush current will stay at around 1 p.u. (per unit) when the closing angle varies ± 20° from the optimum switching moment. A similar curve exists for each possible flux pattern in the transformer, and the role of the CSD is to energize the power transformer at the optimum instant.

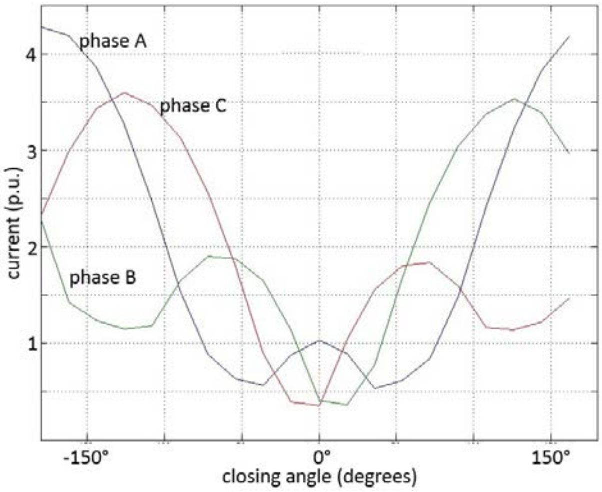

Fig. 2 Inrush Current vs Closing Angle Deviation

When a power transformer is not loaded, it is possible to control its flux pattern to a known value by opening the CB at a fixed instant and then close the CB at the optimum instant that minimizes the inrush current for that flux pattern. However, this technique cannot be used in subsea applications because the uncontrolled de- energization of the transformer may be due to a loss of power in the umbilical from the topside, resulting in an unknown residual flux pattern. Therefore, the successful mitigation of the inrush current at all times using a CB with simultaneous pole operation is only possible if the residual flux resulting from the previous transformer de-energization is measured by the CSD.

B. Basic device operation

Fig. 3 illustrates a typical CSD installation in a power transformer application. The unit can be seen as a synchronization relay inserted between the commands (CB On Off) and the CB control coils. The CSD is powered from the same DC supply as the CB. Protection relays are connected directly to the CB trip coils because the CSD is slightly delaying the CB commands in order to synchronize the CB operation to the power system waveforms. In power transformer applications, both the closing and opening commands are synchronized to the umbilical voltage measured using a resistive or capacitive voltage divider (Vs). The load current (I) is also measured using a Rogowski coil or a toroidal CT to determine if the CB operates properly as planned, which is equivalent to a 50BF (breaker failure) protection function.

The transformer residual flux is computed from the transformer voltage measured using a 3-phase resistive or capacitive voltage divider connected at its primary winding (VL). The use of magnetic flux sensors inside the transformer core is to be avoided because that solution is intrusive. Each time the transformer is de-energized, the residual flux is calculated from the transformer voltage. The resulting residual flux pattern determines the optimum closing instant of the CB to mitigate the transformer inrush current.

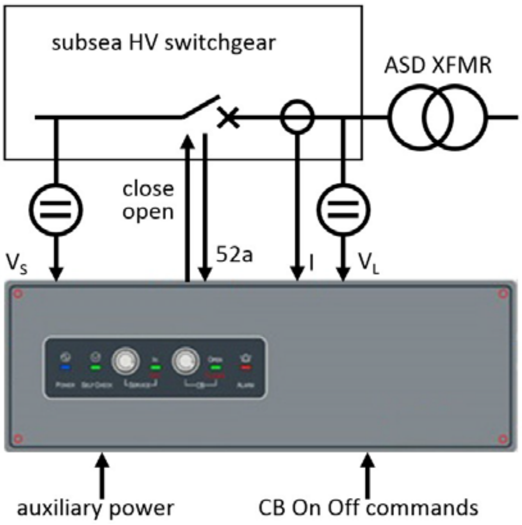

Fig. 3 Typical CSD Installation

Since the CB characteristics are closely linked to the accuracy of the switching operations, one CSD is required at each CB to be controlled. For high availability applications such as subsea installations, redundant units can be connected in parallel to the CB. Should a CSD need to be replaced, the residual flux pattern information can be retrieved and uploaded to the replacement device.

III. SUBSEA ASD CONSIDERATIONS

The ASD of Fig. 4 uses current source technology (CSI) which does not have a capacitive component either in the rectifier or the DC link. When the ASD is energized by closing the ASD transformer incoming CB, the inrush current is limited to that seen by the transformer and the snubber components of the ASD which are insignificant. This avoids the need for a pre-charge circuit typically required by voltage-source drives (VSI) which have a capacitive DC link.

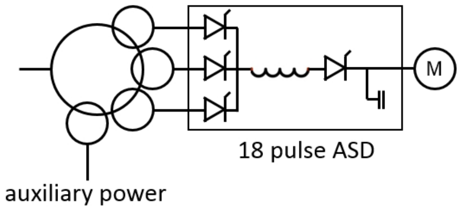

Fig. 4 Current Source ASD

There is a machine-side capacitor which is connected at the output side of the ASD. This capacitor is energized only after the ASD commences gating and the current is inherently limited by the ASD so that the rate of charge is controlled by the active front end (AFE) rectifier and DC link inductor which are inherent to this topology.

VSI drives, as mentioned earlier, typically have a large DC link capacitor. In order to limit or control inrush to the DC link capacitor when first energized, some form of pre-charge circuit is required. For drives with passive rectifiers (DFE), this pre-charge circuit is typically an impedance which is in series with the drive power circuit. This impedance is bypassed after charging of the link capacitors has been completed. This solution was used in the Ormen Lange pilot project by inserting an impedance in the HV circuit to the subsea ASD.

Recently, a number of HV VSI drives have come out with rectifiers utilizing AFE technology. These topologies typically make use of an LCL (inductor, capacitor, and inductor) configuration ahead of the active rectifier which will result in an inrush on energization with the magnitude dependent on the sizing of the capacitive and inductive elements of the circuit. Depending on the particular topology, an external pre-charge circuit may or may not be required.

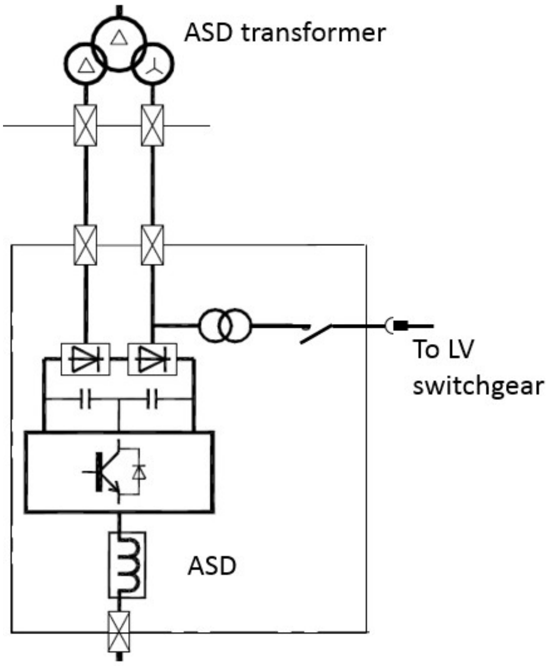

Fig. 5 LV ASD Capacitor Charging Circuit

Another solution is charging the capacitors via a LV connection as shown in Fig. 5. Since the capacitor charging must be done prior to energization of the ASD an auxiliary AC power source is required. The tertiary winding of transformer T1 will provide AC auxiliary power subsea as soon as it is energized. This power via the LV switchgear is used to charge the VSI drive capacitors.

One disadvantage of this solution is that a failure in the LV circuit between transformer T1 and the LV switchgear could result in a total shutdown. Redundancy can be achieved by installing two tertiary windings and having redundant LV switchgear with interconnections between them as shown in Fig. 6.

Another possibility that avoids tertiary windings on T1 is to use a VSI drive that uses the DC link capacitor inrush current limiting LCL described above. This solution would need to be studied to see if feasible for use subsea. The advantage of this circuit is that the tertiary winding shown on T1 could now be changed to be on the ASD transformer T2. Since the pre-charging is internal to the ASD, it can be switched on directly without use of any external pre-charging circuit or power supply. Typically, more than one subsea ASD would be used and this would provide more than one source of subsea AC auxiliary power for other loads as well (equivalent to having dual tertiary windings on T1). A single failure in the subsea LV distribution system would not result in a loss of production.

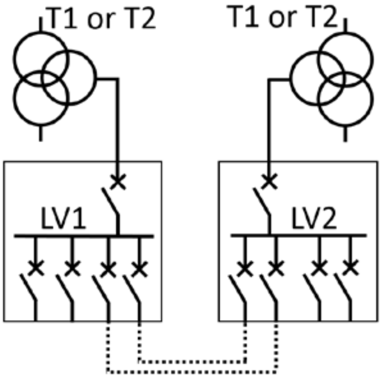

Fig. 6 Subsea LV Switchgear

Fig. 6 shows a subsea LV auxiliary power distribution. The power comes from tertiary windings, either from T1 or T2 depending on the solution adopted for ASD capacitor charging. A separate LV switchgear module is provided for each power source to enhance availability. Also, the LV switchgear are interconnected via redundant circuits to provide additional operational flexibility.

A failure upstream of the incoming LV CB need not result in a loss of the LV switchgear, nor the transformer. It is possible to disconnect the LV cable from the tertiary winding and place a voltage-withstand cap to isolate the tertiary winding LV connection from seawater. The transformer can be energized and supply power to the process loads in this configuration. The LV incoming CB must be tripped and power to the LV bus can be obtained using an interconnection circuit with another LV switchgear module.

In both of these solutions, DC control power is provided to the ASD and LV switchgear via the low-power DC link from shore as shown in Fig. 1. This power is used to supply the part of the ASD control system needed to be able to communicate the status of the ASD prior to energizing it. It also provides the status of the LV switchgear and allows reconfiguration of the main LV CBs prior to energizing any transformers. This is part of the black-start function and can be implemented whether tertiary windings are on T1 or T2.

Installing an HV ASD subsea is a very good option should there be little space available topsides for the equipment. Where space is available however, it is cost effective if the ASD can be installed topsides. For longer step-out distances, the ASD output voltage is stepped up and a subsea transformer installed at the load to lower the voltage. The main challenge in such systems is designing the ASD to be able to correctly control the motor with long cables between them. Progress has been made over the last several years, and the step-out distances for which this system can be used have increased. Use of lower frequency systems (16 2/3 Hz) can also help extend this distance.

AUXILIARY POWER SYSTEMS

Auxiliary power is required for all process systems. Part of this is for the black-start function mentioned earlier. Prior to switching on the main power of a subsea system by energizing the power umbilical, it is first necessary to know the status of the subsea equipment, and be able to change the configuration of the HV and LV switchgear prior to energization. The power requirement for the black start function is very small but must be independent of the main power supply. Most of the other auxiliary power supplies are required prior to energizing process equipment, but this occurs after the main power has been turned on.

For the black-start function, auxiliary power is transmitted directly from the shore station by means of a low-power HV DC system. The DC cables will be installed in the power umbilical together with the main AC power cables and the optical fibers required for the communication and control systems. This HV DC system can be energized and communications established without energizing the main power. This enables the status of subsea switchgear to be determined and modified if necessary by tripping or closing HV and/or LV CBs prior to energizing the main AC power umbilical. Thus, black-start auxiliary power is available without the need for added complexity in the form of a subsea UPS. The use of low-power HV DC for subsea process control has been in use for several years.

A. General DC System Description

The subsea auxiliary power system will receive power via small DC cables operating between 1.8-10kV depending on the required power and step-out distance. At the subsea location, DC/DC converters and power supplies will reduce the voltage to a general low voltage system bus level which can then be distributed to various loads via local power supplies and DC breakers as shown in Fig. 7.

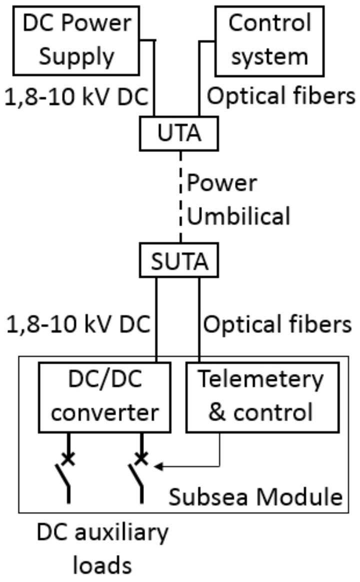

Fig. 7 Subsea DC Distribution

This DC power supply is completely independent of the main AC power supply and thus can provide power to the subsea telemetry & control and auxiliary equipment prior to energization of the main power system. The DC and fiber optic cables are integrated into the power umbilical as shown in Fig. 7.

Fig. 7 does not show any redundancy. Typically dual DC and optical fiber cables are provided, each connected to separate subsea modules. Any subsea module can be disconnected and replaced without loss of the other module, thus avoiding any loss of production.

B. Power System Auxiliary Loads

The DC system bus is routed to allow for power delivery to two main types of loads. The first of these is power system auxiliary loads, the principle ones being the HV and main LV CBs, protection relays, CB control equipment and the communications system.

As shown in Fig. 8, separate DC power circuits are provided for each subsea HV CB. Circuits A and C provide power to the CSD and protection relay, circuit B provides power to the CB trip and close coils, and circuit D supplies the CB spring charging motor. It is thus possible to monitor and control each HV CB without having energized the main AC power cable to the subsea location. This provides operators with the black-start capability.

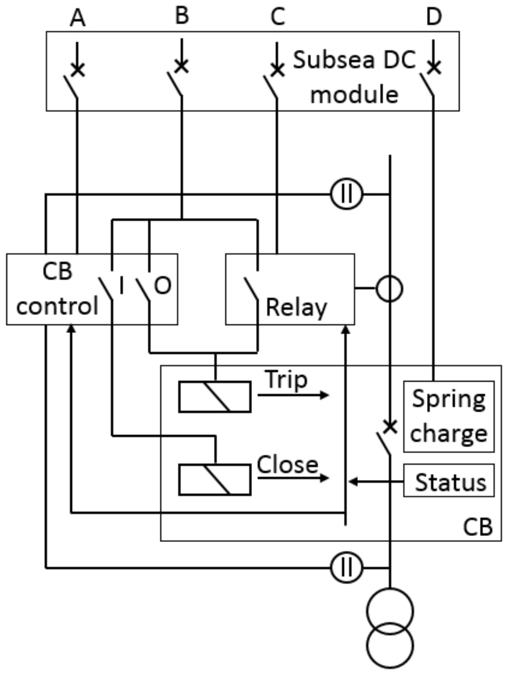

Fig. 8 Auxiliary DC Power for HV CBs

C. Process System Auxiliary Loads

The second type of DC loads are small process loads that may need to be operated prior to energizing any of the main subsea loads. Such loads could be motor operated valves (MOV) or lube pumps. The DC power system can be designed to provide the power for such small loads prior to energizing the main power circuit to the subsea facility. A separate DC circuit can be provided for each of these loads.

For small loads that require an AC power supply, a DC/AC converter is provided. For small intermittent loads, the DC auxiliary power system can supply the power without the need for a battery. Should the power requirements be larger, then either the DC auxiliary power system capacity must be increased, or for intermittent loads, a subsea battery is required. The battery is trickle charged by the DC supply and after charging, the energy necessary to power the process load is provided by the battery.

D. Magnetic Bearings

Magnetic bearings are often used subsea since there is no wear because the bearings float in a magnetic field. The power supply to magnetic bearings must be very reliable since loss of power results in bearing contact. The bearing supply must be available prior to starting the motor, and must remain energized until the motor has come to a complete stop after switching off. Since one cause of switching off a motor is a complete loss of power, some stored energy is required to allow the motor to coast to a stop in such conditions.

Two different solutions have been implemented to date. One uses redundant subsea UPS to provide the power, and the other redundant UPS at the shore station, each having an individual cable to the subsea template. Another possible solution is using normal AC auxiliary power as described above for operation, and a subsea battery trickle charged by the DC control power link for emergency stop conditions. When there is loss of power, the battery is discharged into the magnetic bearing control system providing the energy necessary during coasting down. Since magnetic bearings normally required DC power, such a solution could be cost effective.

IV. TELEMETRY & CONTROL

All telemetry and remote control is provided via optical fiber connections. The subsea facility is connected to the topsides control system via fiber optic cables integrated in the power umbilical (Fig. 7). The auxiliary power required for the subsea communication and control system is provided by the DC from shore auxiliary power system as described above. Although not shown in the Figs. each device that must respond to control signals or provide information will be connected via an optical fiber.

The general practice for subsea process systems is to execute all control orders topsides. The subsea equipment will respond to these orders but, with the exception of protection relays will not act on its own.

All equipment deployed subsea must be able to communicate via a non-proprietary communication system that provides reliable and high-speed communication with the topsides control system. Although it is very common in topsides installations for the power system control and process control to be done by two independent systems, it makes sense for subsea applications to attempt to do both with the same system. Less hardware should result in a reduction of the number of possible failure modes.

V. SYSTEM REDUNDANCY

Redundancy is often seen as a means of increasing the availability of the complete system. Failure of a single device should not cause a loss of production. Redundancy is however a double-edged sword. Increasing the number of components and the additional interconnections can actually reduce the overall availability of the system. Sometimes it is also found during commercial operation that a process shut down is required to retrieve a faulty module that is being replaced, even though the redundant module is operating satisfactorily. Great care and diligence is required when designing redundant systems to avoid such unpleasant surprises.

Avoiding common modes of failure is a good starting point in the design of the systems. Some common modes of failure will continue to exist however, and their influence on availability must be carefully considered. The HV CB itself can have a mechanical fault causing it to stick in the open or closed position. A leak in a subsea module can allow sea water to enter and result in the loss of a substantial part of the subsea facility. Mechanical damage from equipment accidentally dropped into the sea above the facility can cause extensive damage.

A. DC Auxiliary Power Supply Redundancy

It is possible to design the DC auxiliary power system, the telemetry & control system, and the protection system such that there are no common modes of failure. The redundant DC/DC converters, DC breakers, power supplies and protection relays are housed in separately recoverable modules [2]. This decreases the Mean Time To Repair (MTTR) thus enhancing the overall availability. The modules can be disconnected and retrieved without requiring a process shutdown. If dual DC auxiliary power cables are provided for redundancy, consideration should be given to installing one cable in the power umbilical and the other one in the control umbilical or separate cable. The same applies to the fiber optic cables.

All connections between auxiliary power supplies and switchgear are made via wet mate connectors. In some cases it may occur that the removal of a control module may result in a subsea connection remaining energized and being exposed to sea water. In such cases the system is designed such that this cable end will terminate in the female connector. Since the conductor of the female connector is normally covered by oil or some other insulating fluid, it will not be in contact with sea water and can remain energized when in the disconnected position. An example of this is the signal on the terminals of a low power current transformer (LPCT). If a redundant protection relay is retrieved, the terminals of the LPCT remain energized since current is flowing through the primary winding. The voltage levels are small (< 1 V) and thus connection to the female wet mate connector allows continued operation even with the main power circuit energized and drawing current.

Where redundant control equipment is implemented, it is necessary to be able to independently shut of the auxiliary power to control outputs. Thus, if a device fails in such a manner as to emit unwanted control signals, these can be neutralized by switching off the auxiliary power to the output circuits.

B. CB Control Redundancy

Fig. 8 shows the basic scheme for controlling a CB. The protection relay's main function is tripping the CB under fault conditions and the CSD (CB control device in Fig. 8) does the normal closing and opening. Protection relays can be selected and configured such that each relay can fully control two CBs, thus providing redundancy without adding additional devices. Failure of one relay does not result in any loss of production.

To achieve redundancy for the CSD, it is necessary to install two devices per CB. By controlling the power supply to the CSD output contacts, it is possible to isolate a faulty CSD and prevent it from closing or opening a CB due to mis-operation. Normal operation would be with one CSD, the other one having the power supply to its output contacts isolated. Each CSD would be installed in a separately retrievable subsea control module to allow replacement while the other module continues to operate. The use of LPCTs and low power VTs provide measurement outputs that could be exposed to sea water by connection to female wet mate connectors thus allowing the main power circuit to remain energized.

C. Process Redundancy

Redundancy considerations for critical loads will often involve redundant power supplies. Some equipment will have two auxiliary power connections, each one being supplied by completely independent power supplies. The load must be designed such that no failure of one power supply will result in the incorrect operation of the other. Magnetic bearings is one example of such equipment.

D. LV Switchgear Redundancy

A possible solution to achieve redundancy in the LV distribution is shown in Fig. 6. Some applications have dedicated HV cables and step-down transformers to provide a redundant LV subsea power distribution. Such a system was provided for the Åsgard subsea compression station. This is feasible in shallow water and when the step-out distances are not too long. For deep-water applications the cost of such a solution could be prohibitive.

E. Telemetry & Control Redundancy

A dual-redundant control system architecture is normally used for subsea applications. Completely independent systems having no common mode failure points are to be used. Single device failure should never result in loss of production. This includes the auxiliary power supplies for the dual-redundant control equipment.

VI. INSTALLATION AND COMMISSIONING

One of the key factors in designing subsea electrical systems is modularization. Having several modules makes it easier to retrieve equipment that needs to be repaired or replaced, and in many cases this can be done without having to stop production. The main disadvantage or modularization is that it increases the number of wet-mate connectors required as well as the total number of penetrators. Additional equipment means additional possibilities for failure. Failure of a penetrator could let salt water into a subsea enclosure causing a major disruption in production.

After the modular design has been finalized, it is necessary to consider installation of the equipment. ROV access is required for connecting and disconnecting modules, but ROV access is also a potential cause of failures since ROVs can damage equipment. The layout of the subsea modules should be designed to provide the best protection against falling objects and poor ROV maneuvering.

The design of the flying leads connecting subsea modules is also a challenge. Often the male connector is simpler in design than the female connector and thus less prone to failure. It is thus probably best to install the female connectors on flying leads which could be retrieved for maintenance. Avoiding retrieval of subsea modules should be one of the main design criteria.

Submodules should also be considered. A submodule is integrated into a larger module allowing access to parts that may have a shorter design life, thus permitting their retrieval and leaving the main module in place. This technique can be used for electronic devices such a protection relays and communication equipment.

$$Availability = \frac{MTTF}{MTTF + MTTR}$$

The installation design must also take into account how the system will be tested and commissioned. ROV access is key to successful commissioning; however, designing safe ROV access to the equipment is a difficult task. Also, consideration must be given to possible damage to installed equipment when handling the modules yet to be installed. Dropped items can destroy installed equipment.

Testing prior to commissioning is important but is not easy for subsea systems. A comprehensive test plan is required at the start of the design phase in order to be sure that the required tests can be conducted during installation and after installation is complete. This may influence the design of the equipment. All test equipment is to be defined during the design phase.

VII. MAINTENANCE, ASSET MANAGEMENT

A. Availability study

The design of the system is based on an availability study. The starting point of the study is defining the functional requirements of the system that must be fulfilled at all times. For subsea power distribution this is the aptitude to supply sufficient power within acceptable limits of voltage and frequency to the subsea loads.

The availability is defined as many considerations into account when defining the redundancy that is to be used in a particular system. The availability study should be able to determine which amount of modularity, with and without redundancy will bring the most benefit.

The physical location of the modules is also important in reducing down time. When modules are retrieved and deployed, it may be necessary to shut down the process if the modules are located close to other equipment. Damage occurring during retrieval or deployment could result in major environmental damage should the process not be shut down. Process modules that are designed to be retrieved periodically should be located remote from the rest of the process. If this is achieved, it will not be necessary to shut down the process when retrieving such modules.

B. Maintenance strategy

The maintenance strategy must ensure that the minimum requirements that were used in the availability study are met during the design life of the installation. Due to the modular nature of subsea installation, the strategy should include the following concepts:

- Modules: One spare module of each type is required. It shall be kept in working order so that it can replace a faulty module without delay. It is necessary to determine the best storage conditions as well as any requirements for periodic testing, permanent energization or condition monitoring.
- Components: Spares of all components used in the application are required. Since it may not be possible to replace obsolete components with newly purchased spares due to the constraints of installation within compact subsea modules, it is necessary to have an obsolescence strategy to avoid having to purchase different components. In

where MTTF is the Mean Time to Fail, and MTTR is the Mean Time to Repair. Availability studies will provide the probability of meeting the functional requirements for different possible system configurations. Comparing different solutions is possible by evaluating the failure probabilities for each. Since improbable events happen, an availability study cannot be considered to guarantee a particular result.

As can be seen by the definition, there are two ways of having high availability. The first is to have a high value of MTTF. The second is to have a very low value of MTTR. [3]

Achieving a high MTTF requires the use of reliable components having a proven track record. Their failure rate, expressed as λ (lambda) is generally known. In addition to using components having a very low λ, it is also possible to increase the MTTF by adding some redundancy as discussed above. Hot swapping should be strived for any time redundancy is provided. Adding redundancy requires an extensive system analysis since redundancy generally means more components and thus more failure modes. Common mode failures are often introduced unknowingly when designing redundant systems. The complexity of redundant systems is higher than non-redundant systems making operations more difficult. Many failures are the result of operator errors so complexity can even offset the advantages redundancy can bring.

Complex systems are also more difficult to maintain and are more costly. Thus it is necessary to take addition to the hardware, this strategy should include all software, firmware and configuration files for the components as well as ensuring that the machines and software necessary to use the component software are available. The versions of all software, firmware, configuration files and user software that are necessary for refurbishment of any module and repair of any component at any time during the design life are required.

- Repair shop: A repair shop capable of refurbishing each of the modules is necessary. This includes all tools, handling equipment, storage space and skilled workmen.

- Warehouse: A warehouse in which all components required for refurbishment can be stored is required. The warehouse could also be used to store the spare modules. If it is decided that any spares need to be energized during their storage, then the warehouse shall be equipped with all necessary power supplies. It is recommended that the warehouse serve as the repair shop as well to simplify the maintenance procedures.

One of the main problems will be ensuring the availability of skilled personnel. A program must be defined to ensure that there is a minimum staff of qualified technicians and engineers in order to refurbish any equipment. It is necessary to define the training program required to ensure that the necessary competence is available at all times. Training equipment and simulators should be considered in this program.

VIII. SIMULATIONS

For grass-root projects, simulations and calculations are the only tools available to engineers. Subsea installations with long step-outs have very particular characteristics which makes it difficult to base a new design on existing systems [4]. Simulations are required to validate new designs.

IX. CONCLUSIONS

It is possible to provide auxiliary power for subsea processing prior to the energization of the main power system. This black-start function allows operators to ensure that the subsea system is in the right configuration before energization.

It is not necessary to implement complex and costly systems to pre-energize subsea power transformers or precharge the capacitors of subsea ASDs. Controlling the closing time of standard CBs eliminates transformer inrush current issues. The drive topology utilized is another major factor which will impact the inrush which will be seen by the system. The current source topology given in the paper minimizes inrush by the inherent design while voltage source drives typically require a pre-charge circuit. Tertiary windings on the subsea transformers and the possible use of a voltage source drive with DC link capacitor inrush reduction modules are means that can be implemented to avoid capacitor damage.

The modularity of the design is a key factor that influences almost all aspects of the application. A detailed availability study can help determine the optimal modular design. The maintenance strategy is a key factor when estimating the availability of the different possible solutions.

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XI. VITA

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