Power Delivery to Subsea Cabled Observatories

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Abstract - Subsea cabled observatories are Direct Current (DC) powered scientific infrastructures connected to the shore via long telecommunications cables. Long cable runs are susceptible to voltage transients during startup, power down and load changes caused by the reactive components of the cable. This problem affects both the medium voltage supply (up to 10 kVDC) to the nodes and intermediate voltages (around 375 VDC) distributed from the node via long cables to secondary nodes. This paper describes the use of DC power via long cables and the potential for transients created in the cable. Systems implemented to understand, test and mitigate these effects are then discussed. Transistor based over-current control and over-voltage protection are shown to offer significant and predictable protection to systems over traditional passive components. A case study is provided on the intermediate voltage used to supply power to the NEPTUNE Junction Boxes from the NEPTUNE Node.

I. INTRODUCTION

Subsea cabled observatories [1] powered from Direct Current (DC) via many kilometers of cable, have to deal with severe voltage transients during startup, power down and load changes caused by the reactive components of the subsea cable [2],[3],[4]. This problem affects both the medium voltage supply to the nodes along with intermediate voltage distributed from the node via long cables to secondary nodes and Science Instrument Interface Modules (SIIMs). This paper describes the use of DC power via long cables and the potential for transients created in the cable. Systems implemented to understand, test and mitigate these effects are then discussed. A case study is provided on the intermediate voltage of 400 VDC used to supply power to the NEPTUNE Junction Boxes (equivalent to SIIMs) from the NEPTUNE Node (Figure 1) [5].

II. BACKGROUND

A cabled observatory is a subsea infrastructure providing power and communications to oceanographic science instruments located at multiple locations up to several hundred kilometers offshore. An observatory normally has shore based power feed equipment (PFE) at a convenient cable landing location.

A standard telecommunications cable supplies power and communications to subsea nodes. Nodes convert the supplied power to working voltages suitable for further distribution or for directly powering instruments (Figure 1). Nodes also distribute and / or convert the fiber optic communications.

Cabled observatories are currently being developed and deployed by scientific communities around the world [1] to provide greater understanding of the world oceans and marine ecosystems.

A. Power requirements of cabled observatories

The deployment of a cabled observatory is a major financial commitment by a funding organization and consequently will be expected to have a long and reliable life. Therefore, the two services provided by an observatory, power and communications, must have the potential to supply not just the current science requirements, but also the predicted requirements over the 20 year lifetime of an observatory.

The majority of oceanographic science instruments have been developed for autonomous deployment on mooring buoys with battery power and non-volatile memory storage. These deployments may last from several days to a few months and consequently, these instruments will draw little power (a few watts) and provide fairly low bandwidth data (a few bytes per second). However, instruments are already being developed to make use of the power and data available from a cabled observatory: Hydrophones are producing tens of Megabytes of data, continuously operating vertically profiling winches draw several kilowatts of power, hi-definition still and video cameras produce vast about of data and consume hundreds of watts of power for lights and electronics. And Remotely Operated Vehicles (ROVs) are being permanently deployed on the ocean floor to provide real time interaction with the subsea environment. From these early developments, it can be assumed that the data and power required at a cabled
observatory node will continue to increase. In order to meet these immediate and future demands, nodes are being designed to supply between one and ten kilowatts of power.

B. DC Power Transmission

Cabled observatories are powered using Direct Current (DC) as opposed to Alternating Current (AC) for several reasons [6]. Most importantly, a DC system allows the use of a single conductor power cable delivering a negative potential voltage to the subsea nodes. The return path is then formed via the sea water. This has the double advantage of being able to use standard telecommunication cable and the return path has virtually zero losses (as the cross-sectional area for the ocean return path tends to infinity). The cable operates at a negative potential so that the cathode of the return path (which gains material) is located subsea while the anode (which looses material) is located at the shore station, for easier maintenance.

C. Medium voltage transmission efficiency

Power transmission losses in the telecommunications cable limit the power that can be delivered to an observatory node. It is important to minimize these losses in the transmission system and thus increase the power available at the nodes. Transmission losses are minimized by increasing the transmission voltage at the shore station as the fraction of power lost is inversely proportional to the square of the transmission voltage.

In order to supply several kilowatts of power to each node on the observatory, where each node can be several hundred kilometers from the shore station, a medium voltage, typically in the region of ten thousand volts, is required.

D. DC Transmission challenges

Using medium voltage direct current power over long cable lengths presents a number of problems for cabled observatory design. In addition to resistance (R), the single conductor telecommunications cable has capacitance (C) and inductance (L) as well. The effect of this LCR network will cause voltage transients during current changes such as turn on, turn off and load changes. These voltage transients can exist for several milliseconds and can exceed twice the steady state voltage. If not controlled and removed, these transients can damage both source and load electronics.

III. TRANSIENTS PROTECTION

A. Simulation

To predict the magnitude of electromagnetic transients, a series of simulations are run with power systems analysis EMTP based software tools [4] using specialized models for the cable [3], switching functions, source and load. Normal operation events such as turn on, turn off and worst-case rate-of-change for the load are simulated. Additional simulations are carried out for fault conditions such as short-circuit and near-instantaneous load removal (from either a downstream breaker tripping or fuse blowing).

The results from the simulations provide a specification for over voltage protection (OVP) at the load and a soft starting current ramp for turn on at the source.

B. Over Voltage Protection (OVP)

Overvoltage protection can use passive components such as Transorbs and MOVs, but in some cases, the voltage margin between nominal operation and potential damage to electronics can be too narrow for passive protection. The circuit shown in Figure 2 shows an active clamp that can protect the downstream electronics operating close to their maximum operation voltage.

![Figure 2: Over Voltage Protection Concept](image)

The circuit operates like a linear regulator and dissipates the transient energy as heat in the transistor. The simulations are important to calculate the capacity of this circuit and typically, a significant margin is included.

C. Soft Start

A soft start can be designed at both the shore station power feed equipment (PFE) and at the node (for the distribution of intermediate voltage power). By designing the power source to ramp up to the medium voltage over a period up to a few seconds, large inrush current and associated voltage transients can be prevented. A number of methods can be used to ramp the voltage slowly, including PWM control of a semiconductor switch based on measured current.

IV. LABORATORY VALIDATION

As with any system, extensive testing is completed at the factory prior to deployment. However, having several hundred kilometers of armored telecommunications cable delivered to the factory is often impractical. For most deployment scenarios, the first time the complete system will be powered by the telecommunications cable will be at deployment. In order to reduce the risk of problems occurring at this late stage, a physical simulator of the cable is manufactured out of the appropriate resistive, capacitive and inductive elements. This physical simulator of the cable is often rack mounted and requires considerable cooling as...
several kilowatts of power will be dissipated by the resistive elements.

The reactive and resistive parameters defined by the cabled manufacture are grouped into several ‘pi’ blocks for each cable section. This provides a good representation of the cable parameters without making the simulator too complex. Results of the physical simulator are compared to the computer model developed earlier to ensure the cable and systems behave as expected. Additional tests can then be completed to show the effects of soft starts and OVP circuits on reducing and controlling transient voltages during both normal operations and during fault conditions such as short circuits.

A. Intermediate Voltage distribution

The transient voltages effects seen on the medium voltage telecommunications cable are also found on the distribution of intermediate voltage (375 VDC) power from the node to secondary nodes or science instruments interface modules (SIIMs) (Figure 1). The intermediate voltage allows for several kilowatts of power to be transmitted up to 10 km, depending on the size and build of the cable. A seawater return for intermediate voltage distribution is impractical so a balanced conductor cable is used. However, the LCR parameters of these shorter cables can still generate equipment damaging over voltage transients by the same mechanism described earlier.

The following section provides a case study of a NEPTUNE Junction Box (equivalent to a SIIM in Figure 1) that is located 10 km from a node. This analysis, design and testing was carried out at OceanWorks during the first half of 2008.

V. CASE STUDY

The NEPTUNE cabled observatory is used as a case study in this section. The NEPTUNE observatory has an 800 km, 10 kVDC backbone power distribution system. Along the backbone are several 10 kV to 400 VDC, DC-DC Medium Voltage Converter (MVC) located at nodes. Connections from the 400 VDC node ports to Junction Boxes (JBS) where the scientific equipment is connected extends up to 10 km away. In this scenario, voltage transients caused by fast load changes and turn-on current spikes exist and can significantly reduce the lifetime of the intermediate voltage system. Specialized current and voltage control is required.

The system was modeled in EMTP power systems simulation software to understand the severity of inrush currents and over voltage transients. The model consisted of an ideal voltage source, a resistive and capacitive input impedance, an ideal switch, a detailed model of the cable, and a load impedance. The load impedance was modeled as a 20 uF capacitor at the input terminals with a nearly purely resistive component for the load (typical of a downstream DCDC converter). Many of the systems anticipated to connect to the node ports have capacitors at the input stage to prevent voltage drooping at the device terminals. A simplified representation of this system model can be seen in Figure 3.

![Figure 3: Simplified Source, Cable and Load Model](image)

Two simulations were conducted. The first scenario is a “hard start”, meaning that the ideal switch was closed in one time step, the load was set to be purely and the current transient was observed at the source switch. The second scenario is when a significant load is dropped from the 400 VDC bus (Load 1 in Figure 3) and the resulting Voltage transient is observed at Load 2 terminals. To investigate worst case scenarios, the maximum expected voltage of 400 VDC was used.

In the first scenario (turn on sequence) the inrush current rose to 26 A for 1 mS and then dropped to zero (Figure 4).

![Figure 4: Simulated Inrush Current at the Source](image)

In the second scenario (significant load dropping) the over voltage reached a value of 700 V and in some scenarios, was as high as 1000 V depending on the amount of input capacitance at the source (Figure 5). It is difficult to estimate the exact value of the input capacitance little is currently known about the MVC and its transient performance. A value of 20uF was used for these experiments. The transient
responses of the simulations were used to define the voltage and current control requirements.

![Figure 5: Simulated Over Voltage at Load Terminals During Load Change](image1)

Inrush current limiting and over voltage protective (OVP) circuits were then developed. A pulse width modulated FET transistor provides a controlled soft-starting device designed to limit input current surge to 6 Amps. An IGBT transistor over-voltage protection circuit was designed and built to control the voltage transients. The 400 VDC system with the inclusion of the two protective devices can be seen in Figure 6.

![Figure 6: Simplified Model with OVP and Soft Starter](image2)

Testing the 400 V cabling system with the additional protective devices before deployment is not practical due to the size and availability of the 10 km cable. A hardware cable simulator was designed as an approximate model for the long cable lengths. This approximated "multi pi model" was compared to EMTP simulations of a precision cable model (J.Marti Model) and adjusted until the response of the two matched closely. The multi-pi model was then physically built into a rack mountable case. Extensive lab based validation testing could be performed on the junction box and its new protective equipment in the lab before full deployment using this simulator.

![Figure 7: Inrush Current Control Comparison to Soft Starter](image3)

A. Results of Using Protective Equipment

The current and voltage transient tests conducted in simulation were then repeated in the lab. These tests were conducted with and without the OVP and soft start protection.
Three current inrush lab tests were conducted: 1. with a contactor in place of the switch, 2. using a FET transistor switch, 3. with the soft starter system. These three tests are compared directly with the simulation results in Figure 7(a).

In testing the current inrush, the three switching scenarios had significantly different current transients. When the contactor was used, it had the amplitude of the ideal switch simulations peaking at 26A, but the connection also contained “switch bounce” noise as shown in Figure 7(b). When the FET switch was used, the resistive turn on time of the FET system had a less severe current transient that peaked at 17A as shown in Figure 7(c). The soft start current limiter had the most significantly reduced current transient. During startup, the current transient did not exceed the 6 A design limit. This is a reduction of over 4 times of the contactor based current surge as shown in Figure 7(d).

The soft starting current limiter has significantly improved the inrush current and has allowed for sizing of equipment to match the maximum loads and not the non-linear inrush transients.

The test results shown in Figure 7 represent the current inrush at the Junction Box after the 10km cable simulator. If the Junction Box was located closer to the node, the corresponding cable resistance and reactance parameters will reduce and the inrush current will increase. During tests with no cable simulator inline, an inrush current of several hundred amps was observed for Figure 7 scenarios a, b and c. However, the soft start circuit always limits the inrush current to less than 6 amps as shown in Figure 7, scenario d.

Two tests were conducted to validate the Over Voltage Protection circuit: 1. high load to low load change (Figure 8) and 2. light load to no load change (Figure 9). These tests were plotted with the input over voltage transient and controlled output on the same graph to show the change in response.

Tests were conducted by measuring the input voltage of the OVP and measuring the output voltage of the OVP during transients. The switching function of the loads was made with a FET transistor switch.

In both cases, the input transient reaches as high as 750 V but the output of the OVP stays below the 400 V steady state voltage.

In the case of high load to low load transient seen in Figure 8, the output of the OVP appears not to rise to the 400 V set point. This is because the OVP has a slow rise time after the initial transient and takes nearly 500mS to recover from the change.

**VI. CONCLUSION**

Direct current subsea cabled observatories are susceptible to voltage transients during startup, power down and load changes. Proper understanding of the energy held in the subsea cable and the resulting transients is a critical step to prevent the reduction of a system’s lifetime. The reactive components of the subsea cables in the NEPTUNE system affect both the medium voltage supply (10 kV) to the nodes along with intermediate voltages (375 to 400 V) distributed from the node via long cables to secondary nodes and Junction Boxes. The transient effects can be simulated on computers, but computer simulations alone are not sufficient and full-cable testing is logistically difficult. It is therefore useful to construct hardware-based cable simulators that mimic long subsea cables and can be used for empirical testing of transients; using these testing tools, it is possible to design and verify transient suppression hardware with sufficient confidence to deploy without full end-to-end hardware testing.

The intermediate voltage supply to the NEPTUNE Junction Box case study has shown how transistor based over-current control and over-voltage protection offer significant and predictable protection to the subsea system.
REFERENCES


