NEPTUNE Power System: Startup Power Supply for 10 kV to 400 V Dc-Dc Converters

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***Abstract* – NEPTUNE (North-East Pacific Time-series Undersea Networked Experiments) is an underwater power and communications network for scientific experiments. It is proposed for the ocean floor of the Juan de Fuca tectonic plate in the Northeast Pacific Ocean. In the science nodes connected to NEPTUNE network, 10 kV to 400 V dc-dc converters are used to power various scientific instruments and underwater vehicles. The focus of this paper is the startup of the science node converters. The configuration of the NEPTUNE power system is introduced and the challenges of the system resulting from its location on the seafloor are addressed. The set of operations designed to start the 10 kV converters, which includes the control of the 10 kV switches connecting cables to converters, checking faults, and the starting of these converters, is described. These operations require a low voltage startup power supply which obtains energy directly from the 10 kV line. Several commonly used converter startup techniques are reviewed and their capabilities to solving this problem are discussed. Then the proposed circuit design of the startup power supply is presented. The circuit has been implemented and tested. Test results are provided.**

I. Introduction

Oceans occupy 70 percent of the earth's surface and greatly affect global climate, biological diversity, geological activities, and many other global eco-system processes. To understand the complexity and interactive dynamics of ocean systems, data should be collected on many temporal and spatial scales. This poses a great challenge as scientists must build long-term ocean observatories to enable the acquisition of sustained time series data sets. This requires continuous power and communications, which is the main focus of the North-East Pacific Time-series Undersea Networked Experiments (NEPTUNE).

NEPTUNE is a planned cabled network consisting of 3,000 km of fiber-optic/power cable on the seafloor encircling the Juan de Fuca tectonic plate beneath the Northeast Pacific Ocean to provide power and communications to a multitude of undersea observatories [1, 2]. These observatories will allow us the exploration of many oceanographic and geophysical systems in a long-term and real-time approach, which is difficult to carry out using present techniques [3-5].

The NEPTUNE system has two main subsystems: power and communications. This paper addresses one important aspect of the NEPTUNE power system.

The topology of the NEPTUNE system is shown in Fig. 1. The NEPTUNE power system is a network of DC cables energized by two shore stations: one on Vancouver Island in

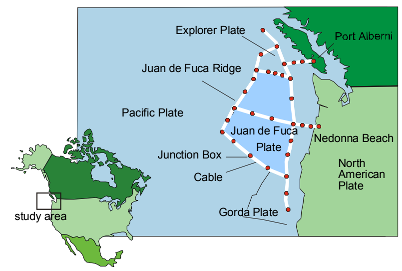


Fig. 1. NEPTUNE cable system

Canada, and the other on the Oregon coast of the USA. The red dots represent branching unit (BU) locations, where different cable sections are connected. Scientific instruments are connected to the network through science nodes, using spur cables coming from the BU's, as shown in the layout in Fig. 2. The backbone and spur cables are standard marine communication cables with both power delivery and fiber optic communication capabilities [6].

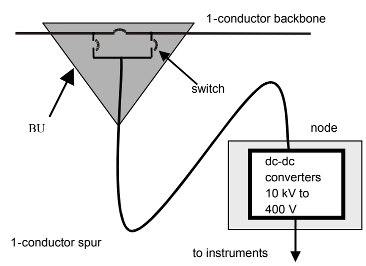


Fig. 2. Layout of science node connection

The NEPTUNE power system is different from the terrestrial counterpart in many ways. In the science nodes, for example, 1) The underwater hardware is difficult to access, therefore every component in the system must be very reliable and maintenance free, 2) No low voltage auxiliary supply is readily available (battery usage is excluded for long-term reliability reason) and 3) No communications exist before the power system is fully operational, which requires the startup of power system to be autonomous.

New methods need to be developed to meet these challenges imposed on the design of hardware, operations and controls of NEPTUNE power system. This paper focuses on providing a solution to the startup of the science node power system, particularly science node converters.

II. Science Node Converter Startup Operations

A. Science node configuration

A block diagram of the science node power system configuration is shown in Fig. 3.

A voltage level of -10 kV was selected for the backbone of NEPTUNE power system [6]. Using negative power supply avoids the corrosion of the electrodes at the science nodes. The 10 kV to 400 V dc-dc converters in the science nodes accept input voltages ranging from -5.5 kV to -10 kV. Outside this range, the converter is disabled. The output of the converter is 10 kW at 400 V [1]. In each science node, there are two 10 kV dc-dc converters with one in cold standby. The converters are connected to the spur cable through high voltage latching switches as shown in Fig. 4.

The initial startup of the science node is controlled locally by a startup and A/B selection circuits. After one of the two converters starts, 400 V and 48 V are available for science loads and internal loads such as power controllers and communications subsystem. Then, the shore stations are able to take control of the system operations remotely.

B. Startup operations in science node power system

The high voltage latching switches S1_A, S1_B and S2 are vacuum type. To extend their life time, the switches are operated only at low power. Besides this, the science node power system has to be autonomous since the communications system is not operational during startup. The challenge is how to inform the science nodes of the intended operation. This problem is solved by using different voltage levels and polarities at the shore stations as communication signals. The startup sequence of operations is performed in conjunction with the shore stations in 9 steps:

1) All switches in Fig. 4 are latched open when the shore station voltage is set to a positive voltage of about 500 V;

2) After a few minutes, the shore station voltage is reversed to about -500 V. This is the signal for switch S1_A to be closed; (The 3 kΩ resistor in shunt with switch S2 reduces the inrush current.)

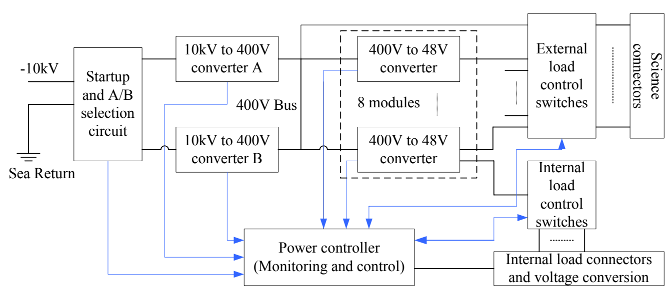


Fig. 3. Science node power system block diagram

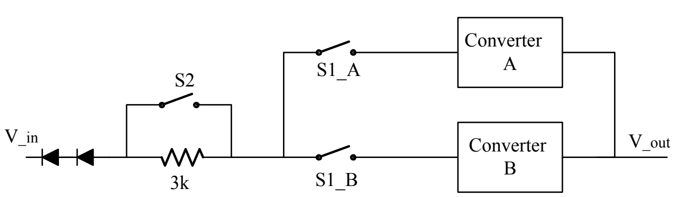


Fig. 4. Science node converters input circuit configuration

3) Fault condition is checked for converter A. If a fault exists, switch S1_A is opened;

4) Switch S1_B is closed;

5) Fault condition is checked for converter B. If a fault exists, switch S1_B is opened;

6) The shore station voltage is increased to -10 kV gradually and switch S2 is closed at -5.5 kV or higher;

7) The control circuit for converter A is powered, and if the output voltage is 400 V, switch S1_B is opened;

8) If converter A cannot start, converter B is turned on and switch S1_A is opened;

9) If converter B cannot start, switch S1_B is opened.

In step 7) to 9), switch S1_A or S1_B is opened at high voltage. This is allowed because the converter is started without any load; therefore, the current flowing through the switches is almost zero.

After the above operations are completed, any fault at the input of the converters is isolated during the low voltage period; if one converter fails to start, it is isolated and the other converter is started. If a converter fails during normal operation, the startup operations are repeated to start the other converter.

To carry out these operations, startup logic circuits are needed, which in turn needs a low voltage power supply to power the logic functions and to provide startup power to the converters. It is referred to in this paper as the converter startup power supply. This low voltage power supply must receive its energy directly from the backbone system when the voltage is in the range of 500 V to -10 kV. The output of this supply is 12 V with reference to the sea ground to power the various logic and MOSFETs' driving circuits. The capacity of the supply is about 0.16 Ws with an energy burst of about 40 W for 4 ms.

Because of the location on the seafloor and the wide input voltage range, the startup power supply in the science node is a challenge to design.

III. CONVERTER STARTUP TECHNIQUES

Generally, a high voltage converter uses a house keeping power supply (HKPS) to power its control and switching actions. However, before a converter starts, HKPS can not provide energy. Hence, there must be a temporary energy source for the control and driving circuit at the beginning. With the switching of power semiconductors in the converter, the HKPS gets its energy from an auxiliary winding of the converter's main transformer or the converter's output. Several methods of starting converters are known [7-10]; they are briefly reviewed below.

In Fig. 5, the control circuit bias voltage is supported by an energy storage capacitor. The capacitor receives its charging current from the input line via a startup resistor. After the capacitor is charged to a preset threshold voltage, the control circuit starts switching. The startup current is provided via both the startup resistor and the bypass capacitor. The voltage on the capacitor will eventually drop because of the discharging action but it must always be above the under

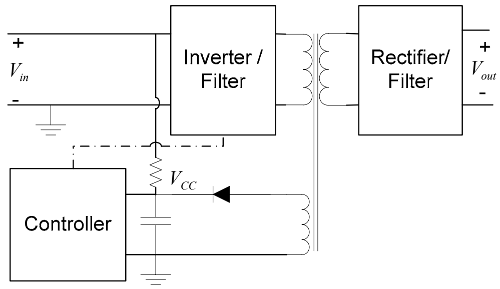


Fig. 5. Converter startup circuit 1

voltage lock out (UVLO) threshold, which is usually several volts lower than the first threshold voltage. The value of the resistor and the bypass capacitor need to be appropriately chosen so that they can supply the control circuit with the maximum required startup current and avoid triggering UVLO. It is easy to see that when large startup current is needed, small startup resistors and larger energy storage capacitors have to be used, which leads to low efficiency and large sized components.

Adding a linear regulator as shown in Fig. 6 improves the efficiency of the startup circuit. Thus, larger value startup resistors can be used and the size of the capacitor can be reduced. But this configuration is not suitable for high input voltage since the transistor must withstand the entire input voltage.

Another method to generate a startup bias voltage involves a relaxation circuit composed of a startup resistor, a capacitor and a voltage regulator in Fig. 7. The RC circuit is followed by a diode ac switch (DIAC). The DIAC blocks the current until the voltage across it reaches its breakover voltage (V_{br}), and then a pulse is generated. The energy in the capacitor is used by the voltage regulation circuit to power the initial switching operations until the auxiliary winding starts to generate output. This method does not require large capacitors or small startup resistors. In addition, the transistors only withstand low voltages. The drawback, however, is that the DIAC ratings are usually small, thus it is not useful when large startup current is needed.

A technique that is more suitable for tapping power from a high voltage input and providing large startup current uses a more complex relaxation circuit [9]. The circuit is shown in Fig. 8. A programmable unijunction transistor (PUT) is used to trigger the thyristor connecting the energy storage capacitor

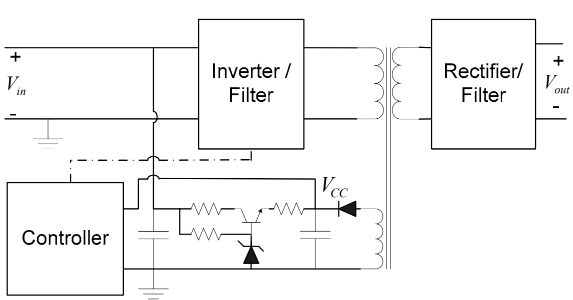


Fig. 6. Converter startup circuit 2

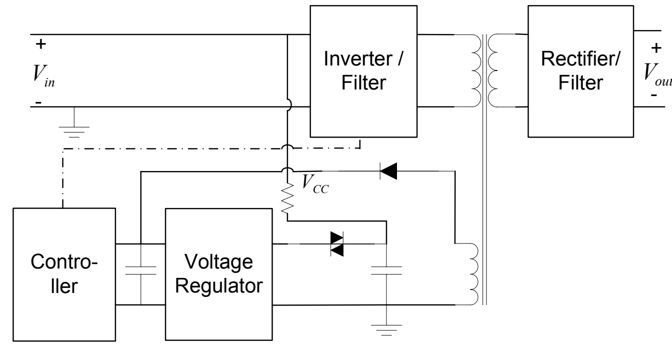


Fig. 7. Converter startup circuit 3

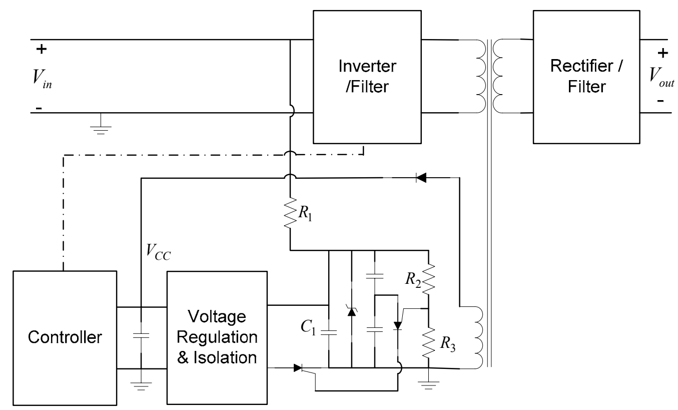


Fig. 8. Converter startup circuit 4

and the voltage regulation circuit. The capacitor C_1 is charged through R_1. When the PUT anode voltage reaches a point set by R_2 and R_3, the PUT gets into its conduction state, and the thyristor is triggered. The voltage regulation and isolation circuit can be a low power forward or fly back converter.

For the 10 kV converters used in NEPTUNE, more than 3 A at 12 V is needed for 4 ms to drive the MOSEFTs of the converters. This is a relatively large amount of power for commonly used converter startup techniques. The 10 kV voltage of the system poses another challenge that requires the use of multiple components or components that can withstand higher voltage. Moreover, the designed operations of the system demands that the startup circuit functions correctly for the range of 500 V to 10 kV.

Among the aforementioned startup techniques, the last one is the most applicable because of its high efficiency and capacity to provide large startup current. However, the circuit is very complex with a large number of components. The reliability is therefore impacted. A new design, which addresses the particular requirements for NEPTUNE application, is described in section IV.

IV. Startup Power Supply Circuit Designed for NEPTUNE

The startup power supply circuit designed for NEPTUNE's 10 kV converters is shown in Fig. 9. The circuit is composed of a relaxation circuit and a linear regulator. The relaxation circuit originally comes from NEPTUNE BU circuit design [6]. With the rectification of D_{11} to D_{14}, at positive voltage, the capacitor C_1 is charged through R_{12} because the diodes D_1 through D_{10} are conducting. At negative voltage, it is charged through both R_{11} and R_{12}. D_1 to D_{10} are small current 2.5 kV diodes put in series to bear reverse voltage at -10 kV. A lower profile can be achieved this way than using bulky high voltage diodes. Resistors R_1 to R_{10} are used to balance the voltage across the diodes. R_{11} is a high value to limit the charging current of C_1. The RC circuit together with the SIDAC forms a relaxation circuit. The SIDAC is a voltage controlled semiconductor switch that closes at its breakover voltage (V_{br}), which is 60 V in this circuit. Therefore, when C_1 is charged up to V_{br}, the SIDAC closes and the energy stored in C_1 is released to the linear regulator formed by R_{14}, D_{15} and Q_1.

A Darlington type transistor is used in the linear regulator because the required collector current is above 3 A. An advantage of using linear regulator is that it can be inherently short circuit proof. From Fig. 9, the maximum base current of Q_1 is determined by R_{14}. When R_{14} is large enough, the emitter current of Q_1 is limited within a safe range. The linear regulator can be replaced with a switching mode power supply to achieve higher efficiency at the cost of increased complexity. This is not adopted since keeping the circuit simple (less parts) and reliable is a much bigger concern.

One difficulty for implementing this power supply circuit is that the SIDAC requires holding current about 50 mA. Normally the control logic circuit for the startup functions does not consume that much energy. One way to solve this problem is to add a bleeding resistor at the output of the linear regulator. But this certainly lowers the power supply efficiency. The approach adopted here is to parallel a normally open switch (K1) with the SIDAC. This switch is operated by the logic circuit and has no holding current requirement. After the SIDAC is closed and the logic circuits are operational, K1 is closed.

The paralleling of K1 with the SIDAC is also solving another problem. Under -500 V, the capacitor C_1 needs to be charged for a much longer time to reach the SIDAC's V_{br} compared with +500 V, due to the difference between the charging resistors. By opening switch K1, the energy in C_1 is maintained. Thus, less charging time is required under -500 V.

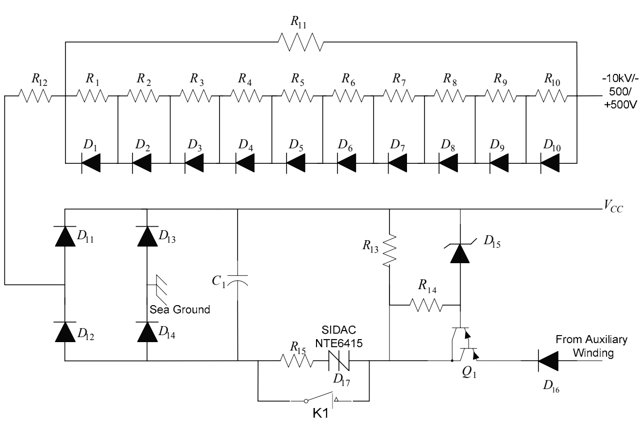


Fig. 9. Startup power supply designed for 10 kV to 400 V dc-dc converters

Under -10 kV, the logic circuit for startup operations is powered by the HKPS. K1 is kept closed, and the voltage across C_1 is determined by the voltage distribution across R_{11}, R_{12} and R_{13}. By adjusting the value of these resistors, the voltage across C_1 can be set at a level much lower than its rating to prolong its life time. The present values of R_{11}, R_{12} and R_{13} are 10 MΩ, 500 kΩ, and 20 kΩ, respectively. The voltage across C_1 is about 20 V after the converter starts. Since it is lower than V_{br} of the SIDAC, the relaxation circuit is no longer functional. This also increases the life time of capacitor C_1 and the SIDAC.

This circuit operates correctly when the input voltage is larger than V_{br}, regardless of polarities. When C_1 is 600 μF, it generates a pulsed power with an interval of about 40 seconds at -10 kV. The ideal waveform of the circuit output at full load is shown in Fig. 10. When only the logic circuits are powered, the pulse lasts for several hundred milliseconds. The test results are shown in section V.

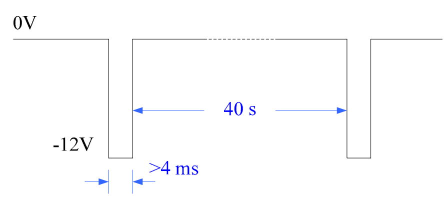


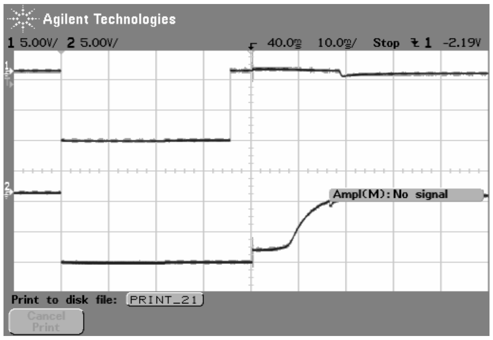
Fig. 10 The ideal output of startup power supply when a converter is being started

V. Test Results

The functionality of connecting a linear regulator to a SIDAC relaxation circuit was tested by Tess McEnulty of University of Michigan in Jet Propulsion Laboratory (JPL), California Institute of Technology. The proposed startup power supply circuit was built and tested at the Applied Physics Laboratory (APL), University of Washington with a resistive load, and in JPL with a real converter. The input voltage in the tests varies from 100 V to -12 kV, a wider range than that required by the operation design. The example waveforms generated by the startup circuit from both tests are shown in Fig. 11 and Fig. 12, respectively.

In Fig. 11, the waveform of V_{cc} drops to about 10 V when a command signal to power the 4 Ω load is made; and nearly 3 A current is drawn from the startup power supply. This high output current lasts for about 8 ms. The period can be lengthened by using a larger capacitor C_1 or employing a SIDAC with a higher V_{br}.

In Fig. 12, the startup power supply is powering the control circuit and the MOSFETs' driving circuit of the converter. The converter consumes about 1/3 of the required startup energy. When V_{cc} reaches its target value, it lasts about 50 ms at 12 V.



Channel (1): Command signal to power the 4 Ω load
Channel (2): Startup power supply output V_{cc}
Fig. 11 Startup power supply output waveform with resistive load

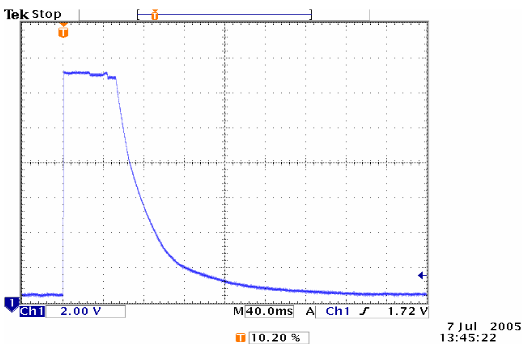


Fig. 12. Startup power supply output when firing a converter at -8 kV (inverted)

VI. CONCLUSION

The NEPTUNE power system poses several challenges in system hardware design, operations and controls. In this paper, the startup operations for the 10 kV converters in science nodes are described. The constraints and requirements for the startup power supply are identified. Commonly used converter startup techniques are reviewed and evaluated. A new startup power supply circuit is proposed. The circuit was built and tested, and the results verified its functionality.

ACKNOWLEDGMENT

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