Undersea MVDC Power Distribution

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***Abstract*— Diversified Technologies, Inc. (DTI) has developed, and is fielding, a significant advance in undersea power network technology using high-voltage, solid-state DC-to-DC conversion. In this architecture, on-shore conventional switching power supplies provide medium-voltage (MV) DC power to several, kilometers-long undersea power cables at 10 kV. At each undersea node where power is required, a medium-voltage, high-frequency DC-to-DC converter down-converts the MVDC power to 375 VDC. Power delivered at this low voltage is available to support a wide range of sensors, electronics, repeaters, motors, or remotely operated vehicles. Since direct connections to the 10 kVDC power cable can be made at any point, and in any potential configuration, down-conversion nodes can be arbitrarily located. This is a significant advance over existing systems, where each node imposes a fixed voltage drop on the cable, limiting the number and configuration of potential nodes. This paper describes the power system architecture, the DC-to-DC conversion nodes, and the status of the initial system development and deployment.**

Keywords: power converter, HVDC, DC-DC, undersea power distribution, high voltage power supply

I. INTRODUCTION

MVDC-enabled networks will provide unprecedented levels of electrical power and high-bandwidth communications to the seafloor over an area hundreds of kilometers on a side. Previous programs, such as Neptune and MARS, have shown that the development of a medium voltage DC-to-DC power converter that allows each node in the network to be powered locally is an elusive technical challenge. In this effort, DTI will use its high-voltage solid-state switching technology to produce a medium-voltage power converter (MVPC), which steps the network's 6-10 kV backbone voltage to 375 VDC in order to power each node locally. An artist's conception of the MVPC is shown in Figure 1.

The network's Shore Power Feed Equipment (PFE) (Figure 2) is based on DTI's 200 kW high voltage power supply (HVPS). Two DTI power supplies are configured in parallel to provide the redundancy that is needed to meet the network's availability requirements. The PFE delivers over 100 kW of DC power to the network backbone at voltages up to 10 kV.

II. MEDIUM VOLTAGE POWER CONVERTER

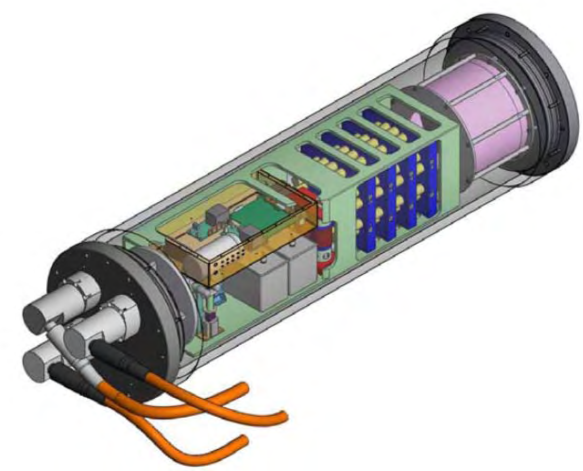

Figure 1 Conceptual drawing of the Medium Voltage Power Converter.

A. Full Bridge Inverter

DTI's MVPC is based on the conventional full bridge inverter topology shown in Figure 3. The topology uses a unique solid-state switching technology, where each switch in the inverter is comprised of a series string of Insulated-Gate Bipolar Transistors (IGBTs) capable of switching 10 kV at peak currents of up to 100 A. The ability of the IGBT switch to open under full load has revolutionized the pulsed power industry, particularly in high power radars, where these switches protect high power RF tubes from arc damage. In the MVPC, DTI's switch technology enables high-voltage, high-frequency switching for efficient power

Figure 2. Layout for the proposed Shore Power Feed Equipment.

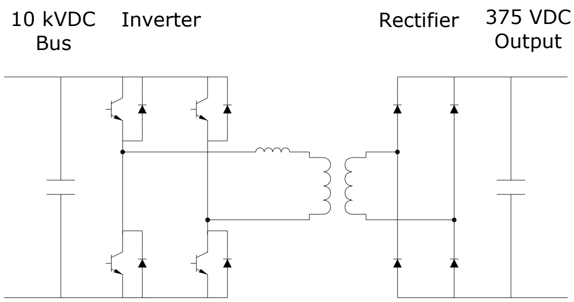

Figure 3. Conventional full bridge inverter topology.

conversion in a compact, rugged package suitable for undersea deployment.

B. *DTI High Voltage Switch*

The key technical challenge in down-converting the 10 kVDC bus to 375 VDC is switching high voltages at high frequency. High-frequency switching is used to minimize the size of the transformer and capacitors, and to provide sufficiently-wide bandwidth for proper load regulation.

The benefits of high-frequency switching must be weighed against switching losses that increase linearly with frequency, as well as size, weight, and efficiency of the switch. Our analysis concludes that an MVPC switching frequency in the 20- to 25- kHz range offers the optimum compromise. IGBTs are the ideal power device for this application because they can handle high power, can be switched very quickly, are rugged, and are highly reliable. By using a series combination of low-voltage IGBTs, switching losses can be minimized while providing sufficient design margin between the IGBTs' voltage rating and the maximum voltage applied across the switch.

Figure 4 shows several DTI PowerMod™ solid-state switch modules. The larger ones are made of 20 discrete IGBT devices connected in series. The gates are driven by inductive coupling to ensure that all transistors turn on simultaneously. This enables the stack to act as a single 10 kV switch without ever exposing a single device to


Figure 4. PowerMod™ high-voltage solid-state switch modules. The larger switches consist of 20 IGBTs in series and are rated for 10 kVDC at 100 A peak current.

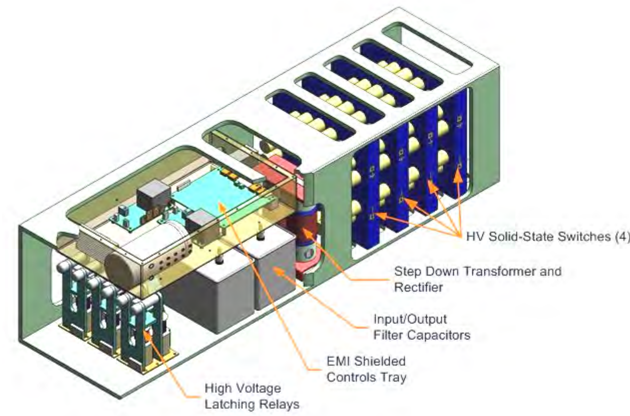

Figure 5. Simplified mechanical layout of the proposed MVPC. Dimensions approximately 48" in length by 10.5" square.

destructive voltages. The switch can commute 100 A (peak) at 10 kV. This is almost a factor of ten above the demands of the MVPC application, and ensures high reliability.

C. *MVPC Mechanical Layout*

The MVPC switches and other components are mounted in a frame and installed into a pressure enclosure. The enclosure is filled with oil to provide voltage isolation and cooling. The mounted assembly is shown in Figure 5. The approximate dimensions are 10.5" square by 48'' length. All of the MVPC control and monitoring electronics, including the switch gate drivers, inverter control board, and data telemetry, are enclosed in the EMI-shielded controls tray.

D. *MVPC Electrical Specifications*

A simplified block diagram of the proposed MVPC is shown in Figure 6. The backbone voltage across the input filter capacitor (10 μF) is chopped by a full-bridge inverter (SW A through SW D) to produce variable-duty 10 kV pulses across a padding inductor (L) and a compact HV transformer. The transformer steps the voltage down by a factor of 10. A diode bridge rectifies the secondary voltage is locked to 375 VDC through a feedback mechanism. A small output LC filter smooths-out most of the remaining ripple.

The inverter's controller makes use of two dynamic quantities: the transformer's primary current and a divided version of the output voltage. The inverter's electronics consists of a phase-shift PWM controller and two gate drivers. The HV switches are driven in pairs (A-B and C-D) to eliminate the possibility of a shoot-through condition. The high-voltage switch stack is comprised of four high-voltage solid-state switches (Figure 4). Control power for both the switch drivers and the power supply controller (~54 VDC and 5 VDC, respectively) is derived from the rectified output of the startup circuit.

Testing of a breadboard inverter at DTI confirmed the following performance specifications:

- 10 kV DC to 375 VDC conversion
- Steady-state power levels up to 20 kW
- Regulation better than 1% into transient loads

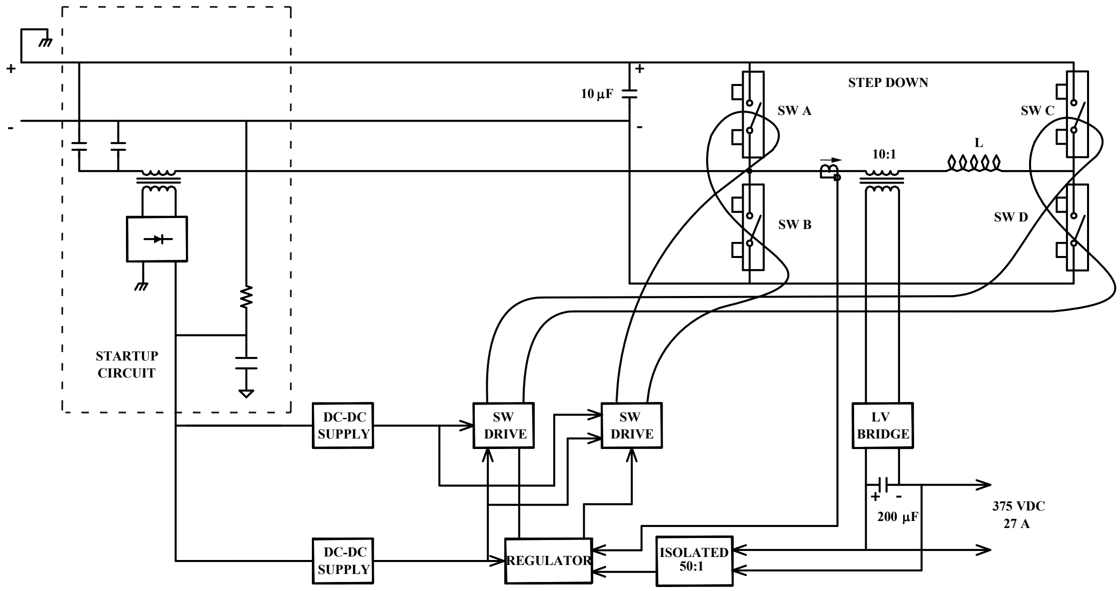

Figure 6. Simplified block diagram of the proposed MVPC.

- Output isolation >> 100 MΩ
- High efficiency: > 90% at high power.

III. Shore Power Feed Equipment

As referenced in Figure 2 and Figure 7, the PFE consists of a set of high-voltage power supplies, a network of power-switching relays, power-distribution nodes, and a control and management system. These components deliver 130 kW of power at 10 kV to the undersea equipment, while fully addressing the need to meet extremely aggressive reliability figures.

A. High Voltage Power Supplies

The main power supplies are two commercial 200 kW, 10 kV DTI high-voltage switching power supplies. They feed off the DC Breaker Panel to power an inverter driving a high-voltage step up transformer, rectifier, and output filter. The power supply inverter uses a phase-shift-control H-bridge to provide low losses and high-frequency switching. The high-frequency switching allows improved dynamic response and reduces the size and weight of the equipment. The inverter is operated using current-mode control, where an inner control loop controls the peak current in the inverter on a cycle-by-cycle basis, and an outer control loop regulates the output voltage and current.

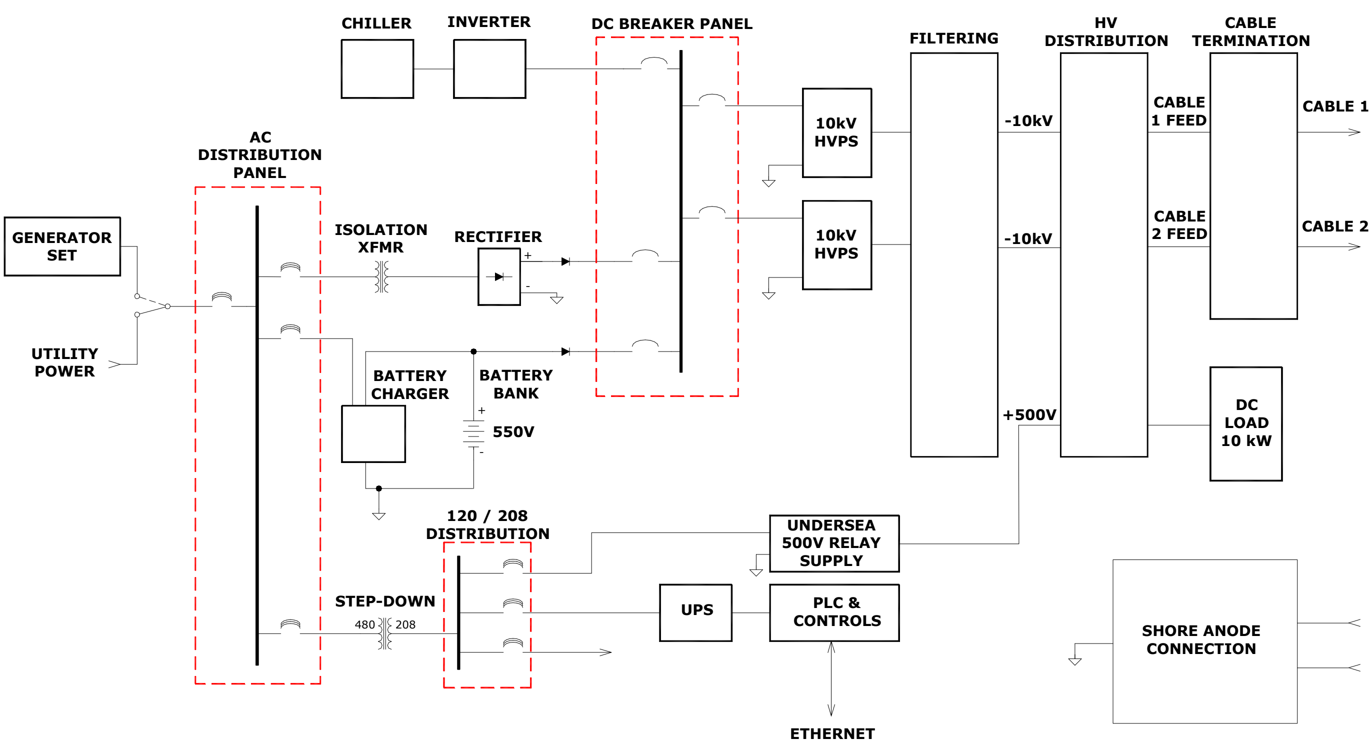

Figure 7. PFE overview schematic.

The mode of operation described above offers a number of performance advantages over other control schemes. The phase-shift control minimizes switching losses by causing the H-bridge switches to close and open under favorable conditions (*i.e.,* minimum voltage or current). In addition, the circuit parasitics are used to aid in switch commutation minimizing the need for snubber networks which tend to be wasteful of power. Current-mode control makes the supply inherently short-circuit-proof and self-limiting; in addition, it can result in improved loop dynamics compared to straight voltage control schemes.

The DTI HVPSs are ideally matched for the PFE application because:

- Current-mode control automatically and inherently limits the supply short-circuit current.
- High frequency switching allows for near-instantaneous shut down, *i.e.,* within one switching cycle, limiting the supply's follow-on energy potential in the event of a fault.
- Wide bandwidth allows for modulation of the output voltage to meet the PFE's cable electroding specification. It also improves the dynamic / transient response of the supply with a minimum of external filter capacitance. This reduces the stored energy in the output, and lowers the potential for energy release into a cable fault.
- The HVPSs' step-up transformer provides complete isolation between the AC prime power / intermediate DC bus and the high-voltage output. This allows the output return to be tied to a separate return / earth ground from the input.

IV. REDUNCANCY AND PROTECTION

A. PFE

The PFE system will interface to a long undersea cable providing power to remote nodes hundreds of kilometers distant. Its redundant design and protection features will maintain high availability and protect the equipment itself.

The system is designed such that each main power supply is capable of driving the entire sub-sea system. The two main power supplies may normally be used in a "one operating, one spare" redundant configuration. Alternatively, both power supplies can be operated with each supply at a lower power level.

The main power supplies are inherently current-limiting, with an additional current regulation loop that reduces output voltage in the event its setpoint is exceeded. These features

Figure 8. DTI COTS 200 kW, 20 kV power supplies.

make the supplies themselves short-circuit proof. In addition, the current in each cable feed is monitored, and a fault here will trigger action to isolate the cable from the supply.

To protect against overvoltage, an internal overvoltage detector in each power supply monitors voltage using a means independent of the main feedback divider, and insures the fault will trip if the voltage feedback loop breaks. In addition, the cable voltage is monitored at the hardware fault controller to provide a second means of protection.

A Programmable Logic Control (PLC) operates the system, and includes both autonomous fault detection and protection for the system. These controls monitor the supplies for internal malfunctions including excessive output voltage, loss of control power, overheating, and gate-driver failure.

B. HVPC

Each node is fitted with the capability to detach its power converter and its outgoing backbone branches from the rest of the network. This is done through normally-closed isolation relays, and it ensures that an undersea fault (*e.g.,* a cable short) cannot bring down the entire system. The relays are controlled from the shore through the power cables themselves.