Undersea MVDC Power Distribution System

Marcel P. J. Gaudreau, Neal Butler, Timothy Hawkey, Kevin Vaughan,
Gerard DelPriore, Noah Silverman, Raul Ramos-Schulze
Diversified Technologies, Inc.
35 Wiggins Avenue
Bedford, MA 01730

***Abstract*— Diversified Technologies, Inc. (DTI) has developed and fielded a significant advance in remote (undersea) power network technology using high-voltage, solid-state DC-to-DC power conversion. These units have been undersea for four years as part of the National Science Foundation Ocean Observatories Initiative Region Scale Nodes. On-shore power supplies provide medium-voltage (MV) DC power to an undersea power cable hundreds of kilometers-long operating at 10 kV and up to 100kW. At each undersea node, electrical power is shared in a parallel architecture with a high-frequency DC-to-DC down-converter at 375 VDC at up to 10 kW. Power delivered at this low voltage is available to support a wide range of sensors, electronics, repeaters, motors, or remotely operated vehicles. Since, in a parallel architecture, 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 alternative serial 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 system development and deployment.**

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

I. Introduction

MVDC-enabled networks 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. **DTI's high-voltage solid-state switching technology is used to produce a medium-voltage power converter (MVPC), which steps the network's 10 kV backbone voltage to 375 VDC in order to power each node locally.** An MVPC is shown in Figure 1.

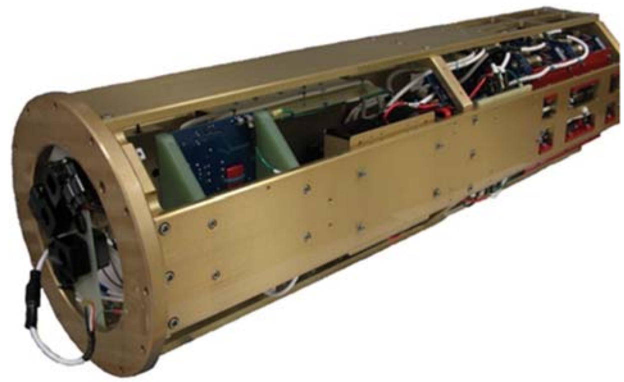

Figure 1. Undersea 10 kW Medium Voltage Power Converter (10 kV to 375 V). These are located in 3km of water 900km from shore.

The power network consists of two major elements: shore-based Power Feed Equipment (PFE) and undersea MVDC converters. The network's PFE (Figure 2) is based on DTI's proven 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 a voltage of 10 kV. 10kW is available at each node.

Figure 2. Installed Shore Power Feed Equipment.

Several scientific discoveries have already been made while relying on the MVPC power system including the real time discovery of an underwater volcano eruption [1,2,3] 300

[1] http://www.washington.edu/news/2015/04/30/seafloor-sensors-record-possible-eruption-of-underwater-volcano/ April 30, 2015 "Seafloor sensors record possible eruption of underwater volcano"

[2] http://www.washington.edu/news/2015/07/15/students-researchers-at-sea-working-on-recently-erupted-deep-sea-volcano/ July 15, 2015 "Students, researchers at sea working on recently erupted deep-sea volcano"

[3] The First-ever Detection and Tracking of a Mid-Ocean Ridge Volcanic Eruption Using the Recently Completed, NSF-Funded, Submarine Fiber-Optic Network in the Juan de Fuca Region", John Delaney, UWash, paper OS41B-06, AGU 2015.

miles off-shore that otherwise would have remained undetected. Figure 3 shows the entire RSN system.

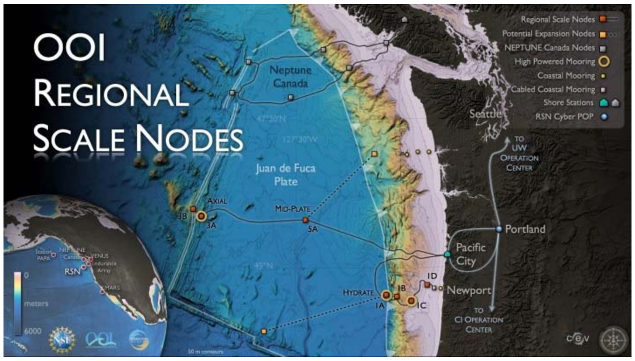

Figure 3. NSF's OOI Regional Scale Nodes off Oregon and Washington west coast. Credit: OOI Regional Scale Nodes Map.

II. SYSTEM ARCHITECTURE

The robust system architecture, pictured in Figure 4, consists of 200 kW of redundant shored-based Power Feed Equipment and up to **10 independently-controllable 10 kW electrically parallel MVPC undersea nodes and is designed to last for 25 years.** Of course, the 10kV bus must remain stiff for all nodes. To enforce stiffness, the shore-based equipment has an ability to control the individual nodes and take them off-line in event of a fault. It can also bring them back on-line. The MVPC is discussed first and then the PFE.

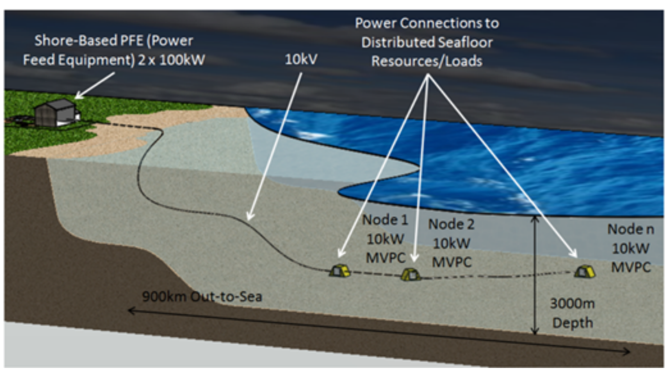

Figure 4. Robust Remote Parallel 100 kW Power Distribution Architecture showing 3 km depth, 900 km out-to-sea and multiple independent 10 kW nodes powering sensors and instruments.

III. MEDIUM VOLTAGE POWER CONVERTER

A. Full Bridge Inverter

DTI's MVPC is based on the conventional full bridge inverter topology. 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 100 A.

The ability of the IGBT switch to open under full load has revolutionized the pulsed power industry, particularly in high power land- and ship-based 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 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 fitting in the small package size demanded by the high pressure vessel for undersea deployment. **At a depth of 3000 m, the pressure is 300 atm = 4500 psi. High frequency switching of the high voltage is required to minimize the transformer and capacitor sizes and to provide sufficiently-wide control bandwidth for proper load regulation.**

Switching electrical losses increase linearly with switching frequency, so the benefits in reduced size and weight of increasing the switching frequency must be weighed against losses and reduced efficiency of the unit. Our analysis showed that an MVPC switching frequency in the 20 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 5 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 destructive voltages. Each switch can commutate 100 A (peak) at 10 kV. This is a current 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 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.

Figure 5. 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.

D. MVPC Electrical Specifications

The backbone voltage across the input filter capacitor is chopped by a full-bridge inverter to produce variable-duty 10 kV pulses across a padding inductor 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 to eliminate the possibility of a shoot-through condition. The high voltage switch stack is comprised of four high voltage solid-state switches (Figure 5). Control power for both the switch drivers and the power supply controller is derived from the rectified output of the startup circuit. Figure 6 shows a submerged node containing an MVPC.

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

- 10 kV DC to 375 VDC conversion
- Steady-state power levels to 10 kW
- Regulation better than 1% into transient loads
- Output isolation >> 100 MΩ
- High efficiency: > 90% at high power.

IV. Shore Power Feed Equipment

As shown in Figure 2 and Figure 8, 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 100 kW at 10 kV to the undersea equipment, while fully addressing the need to meet extremely conservative reliability figures. Presently 6 nodes are active and an average of 17 kW is being consumed with 120 instruments connected, and 200 planned in the near future.[4]

Other uses of this technology include undersea particle detectors[5] and other applications which need robust, reliable power undersea, on land, airborne, or in space.

Figure 6. One of the seven primary MVPC nodes on the ocean floor. Credit: OOI RSN.

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.

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 parasitic characteristics 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.

V. Redundancy 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.

---

[4] Private communication, Dana Manalang, Senior Engineer, Applied Physics Lab, University of Washington, 2/26/2016.

[5] http://io9.gizmodo.com/5870259/underwater-neutrino-detector-will-be-the-second-largest-structure-ever-built

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 current setpoint is exceeded. These features make the supplies themselves short-circuit proof. In addition, the current in each cable feed is monitored, and a fault would 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 cable itself.

Figure 7. DTI COTS 200 kW, 20 kV power supplies.

VI. CONCLUSIONS

Diversified Technologies, Inc. provided a robust power distribution system for the National Science Foundation's Ocean Observatories Initiative with a design life of 25 years.

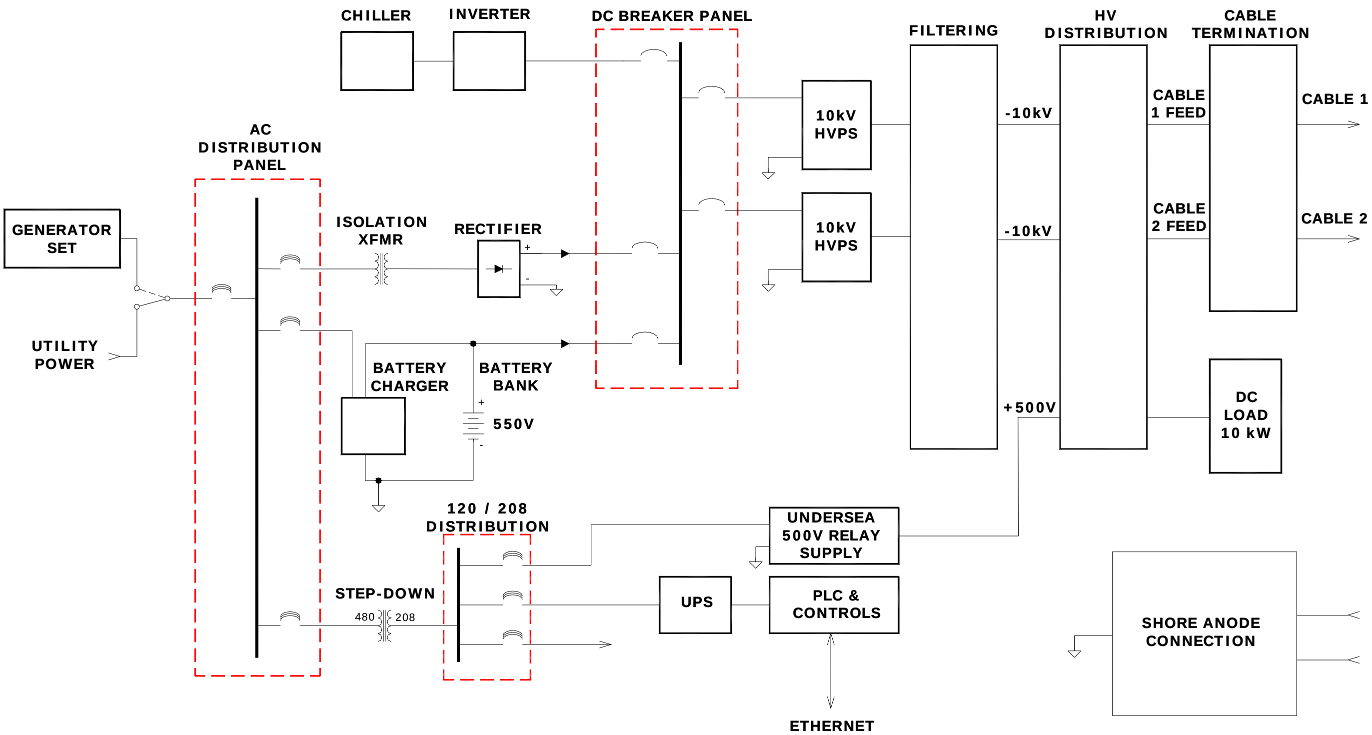

Figure 8. PFE overview schematic.

The power system provides 100 kW at 10 kV and supplies electrically parallel nodes with 10 kW at 375 V and most of it sits in 3000 m of seawater 900 km off-shore. The system has been operating for four years and has provided the power needed for sensors which made several discoveries such as underwater volcanos, locations of hydrovents and many others.

VII. References/Bibliography

1. http://www.washington.edu/news/2015/07/15/students-researchers-at-sea-working-on-recently-erupted-deep-sea-volcano/ July 15, 2015
"Students, researchers at sea working on recently erupted deep-sea volcano"
2. http://www.washington.edu/news/2015/04/30/seafloor-sensors-record-possible-eruption-of-underwater-volcano/ April 30, 2015
"Seafloor sensors record possible eruption of underwater volcano".
3. "The First-ever Detection and Tracking of a Mid-Ocean Ridge Volcanic Eruption Using the Recently Completed, NSF-Funded, Submarine Fiber-Optic Network in the Juan de Fuca Region", John Delaney, UWash, paper OS41B-06, AGU 2015.
4. Private communication, Dana Manalang, Senior Engineer, Applied Physics Lab, University of Washington, 2/26/2016.
5. http://io9.gizmodo.com/5870259/underwater-neutrino-detector-will-be-the-second-largest-structure-ever-built visited 2/25/2016.

VIII. Author Biographies

Dr. Marcel P.J. Gaudreau, PE is President and Chief Technical Officer of Diversified Technologies, Inc. (DTI). He has been responsible for advancing the state of the art in solid state high-power electronics across a variety of applications, including high-power switching power supplies and high-power amplifiers. Dr. Gaudreau earned his B.S. in physics, from the Massachusetts Institute of Technology (MIT) while building a high precision charge monitoring system for the Bates Linear Accelerator. Dr. Gaudreau acquired his M.S. in Aeronautical and Astronautical Engineering at the Charles Stark Draper Instrumentation Laboratory; and Sc.D. in Electrical Engineering and Computer Science at the MIT Plasma Fusion Center in 1981.

Dr. Neal Butler joined Diversified Technologies, Inc. in 2003 as Chief Scientist. Dr. Butler assists engineers with problem solving and good design practices while advocating for and developing new technology areas and improved methods to solve existing problems. One of his primary focuses is increasing the power output and efficiency of switching power supplies, while improving their regulation to < 0.01%. He designed a low stored energy 50 kW, 20 kV to 70 kV supply with < 0.5% ripple and regulation and arc recovery in < 2 ms. He is also involved with several radar power supply control systems including one to improve the regulation to about 60 ppm (3 Volts peak to peak out of 50 kV in a bandwidth of several kHz). He holds a BA in Physics/Math from Wabash College, and MS and Ph.D. degrees in Physics from Purdue University.

Mr. Timothy Hawkey is the Vice President of Engineering at Diversified Technologies, Inc. Mr. Hawkey earned his B.S. in Aeronautical Engineering and his M.S. in Mechanical Engineering from the Massachusetts Institute of Technology. Mr. Hawkey has been at DTI since 1994 and is in charge of the overall management of the engineering staff. He has served as project manager/lead engineer for many major commercial and military programs and advised other military and commercial systems.

Mr. Kevin Vaughan is a Principal Mechanical Engineer at Diversified Technologies, Inc. Mr. Vaughan is currently DTI's lead mechanical engineer in the effort to upgrade the U.S. Air Force AN/MPS-39 Multiple Object Tracking Radar (MOTR), and was previously the lead mechanical engineer in DTI's modernization of the Globus II transmitter and in the design and installation of a 2 MW klystron. He earned his B.S. from the University of Massachusetts at Lowell, and M.S. in Mechanical Engineering from the Worcester Polytechnic Institute, where his studies were concentrated in vibrations.

Mr. Gerard DelPriore is a Senior Electrical Engineer at DTI. Mr. DelPriore draws from a broad based design background including analog and digital hardware, software, power systems and EMI control, much of it applied to the radar and missile fields. He has performed numerous reliability analyses of designed and conceptual systems. Mr. DelPriore received his B.S. in Electrical Engineering from the Worcester Polytechnic Institute (WPI) in 1978 and his M.S. in Electrical Engineering from WPI in 1984.

Mr. Noah Silverman is an Electrical Engineer at Diversified Technologies, Inc. He earned his B.S. degree in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology, where his studies were concentrated in power electronics. Mr. Silverman is a lead system test engineer, and contributes to power systems and controls designs.

Mr. Raul Ramos-Schulze works as an Electrical Controls Engineer at Diversified Technologies, Inc. He received his S.B. in Aeronautical Engineering from the Massachusetts Institute of Technology in 2010. At DTI Mr. Ramos-Schulze led a project to design a 2 MW peak, low-cost, low-inductance switch plate for use in a C-Band radar. Mr. Ramos-Schulze developed a new, modular controls software architecture, which he used to write the controls and user interface code for a recent transmitter upgrade.