

Development and Test of a Medium Voltage Converter for Ocean Observatories

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Abstract- Power system engineering for ocean observatories has been an active area of research and development for the past 10 years. A number of architectures have been reported and discussed, including AC systems, DC systems, constant-voltage systems, constant-current systems, and various series and parallel cable topologies. A sequence of engineering analyses and prototype experiments led the U.S. MARS and the Canadian NEPTUNE programs to select a constant-voltage, branched DC architecture in their systems. A similar power architecture is in consideration for the U.S. Regional Scale Network (RSN). These regional power systems are generally comprised of shore-based power feed equipment (PFE), one or more long (10 – 400 km) single-conductor undersea telecom cables, one or more undersea nodes, and seawater electrodes to return currents from the nodes to the shore. The power conductors in these undersea cabled systems typically have resistances of 1 ohm/km, with operational currents of less than 2 Amps and operational voltages of less than 12 KVDC. High-voltage, low-current power transmission is essential to minimize power losses within the cables and to maintain stability under dynamic, negative impedance loads.

A critical component in regional scale undersea power systems is the medium voltage converter (MVC). The MVC is a DC-DC converter in the primary network infrastructure that receives a medium voltage power input from the PFE via the telecom cable, typically at 1 - 10 KVDC, and provides down-conversion to one or more lower voltage outputs, typically 300 - 600 VDC, to feed power to science nodes and instrumentation in the secondary network infrastructure.

The development of a reliable undersea MVC has been a difficult engineering obstacle in ocean observatories, causing delays and overruns in several projects. Unlike fiber optic timing and data networks, the ocean observatory power system has almost no equivalent terrestrial system market from which to draw mature, affordable, commercial components such as MVCs. The marine technology community has been at various stages of MVC design, development, and prototyping since 2000, trying to solve the difficult electrical, mechanical, and ocean engineering challenges found in ocean observatory systems. These challenges include high-voltage corona and arcing, operational availability, system cost, cable impedance dynamics, instrument load dynamics, thermal dissipation, safety issues, cable and connector faults, installation limitations, and a limited palette of high-quality commercial components for MVC design and engineering.

In this paper, we report the successful development, test, and subsea installation of a 3KV, 3 kW MVC based upon the Vorperian modular stacked architecture. The MVC provides 3000 VDC to 625 VDC conversion for primary undersea networks. The MVC design consists of sixteen (16) DC-DC subconverters wired in a series input configuration, with each subconverter input operating at approximately 187 V (3000V/16). The sixteen subconverter outputs are wired in an 8 x 2 series-parallel configuration, with each subconverter output operating at approximately 78 V (625V/8). A feedback control loop monitors the MVC output and pulse-width modulates the duty cycle of the subconverter switching to maintain precision output regulation.

I. INTRODUCTION

The ocean presents a particularly challenging environment for engineered systems, including crushing pressure, corrosive and electrically conductive liquid, inaccessibility, coldness, darkness, quakes, tsunamis, hurricanes, extreme wave events, thermal vents, landslides, trawling, anchors, shark bites, tangles, and fouling – just to name a few. It is little wonder that the ocean remains largely unexplored, even though it potentially holds a majority of our planet's most valuable food, energy, pharmaceutical, ecosystem, and material resources. Current ocean exploration can be compared to early space exploration – it is hard, dangerous, expensive, and fraught with risks and potential engineering failures. And like early space work, emerging ocean science and exploration is a critically important international endeavor that will significantly impact science, civilization, and nations in the decades ahead.

Power distribution has been one of the most difficult engineering challenges in undersea cabled observatories. Some of these challenges were described in [1] such as negative impedance loads, power load dynamics, long cables, power failures in early system attempts, and an almost total dearth of commercial DC-DC converter products that operate above 400 volts.

To address some of these challenges, a new architecture for medium voltage DC-DC converters (MVC) was reported by the Jet Propulsion Laboratory-Applied Physics Laboratory (JPL-APL) NEPTUNE power team in 2001 [2]. The proposed MVC architecture consisted of a modular stack of lower-voltage pulse-width modulated (PWM) DC-DC converters (a.k.a.

subconverters) with series connected inputs and series-parallel connected outputs. The potential benefits of the proposed MVC architecture included modularity, scalability, reliability, high-efficiency, and readily available commercial components for the low-voltage subconverters. Simulations of negative incremental resistance and dynamic stability in undersea power systems, as well as the idea to use an input filter to dampen and stabilize a stacked MVC, were presented in 2002 [3]. Since that time, a number of ocean observatory projects have reported the development and testing of stacked modular MVCs, including MARS [4] and NEPTUNE [5].

In February 2008, the MARS program installed a 7.25kV-to-400V MVC power supply at the end of a 52-km cable off the coast of California in 900 meters of water depth as the primary power component of the new ocean observatory. The system failed shortly after initial power up, reportedly due to a high-voltage connector problem on the housing. The system was later recovered for repair and reinstallation [6].

In May 2008, the NEPTUNE program office reported the decision to postpone the NEPTUNE system installation until 2009 in order to reduce risks and complete qualification of a 10kV-to-400V MVC for the primary power infrastructure [7].

In this paper, we report what we believe to be the first successful undersea installation and operation of a stacked modular MVC power system. A 3.2kV-to-625V MVC was built in 2007, delivered to the system operator in January 2008, successfully installed in May 2008, and has been in undersea operation for more than a year.

II. MVC ARCHITECTURE

The undersea MVC reported here was based upon the Vorperian architecture and circuit construction proposed in references [2] and [3], and described in detail in 2007 in references [8, 9]. The reader is referred to the IEEE paper [9] for an in-depth treatment of the mathematical theory, models, practical considerations, and developmental testing of the Vorperian MVC architecture.

The design parameters for the MVC are as follows:

• MVC input voltage	2.5 – 3.5 kV
• MVC output voltage	625V +/-1%
• MVC output full power load	3500 Watts
• MVC efficiency	90% typical at full load
• Number of subconverters in stack	16
• Modular stack input structure (primary side)	16 subconverter inputs in series
• Modular stack output structure (secondary side)	2 groups in parallel, 8 subconverter outputs in series per group
• Subconverter input voltage	187.5 VDC typical
• Subconverter output voltage	78 VDC typical
• Subconverter circuit type	Isolated forward converter with synchronous rectification
• PWM switching frequency	40 kHz
• Undersea feed cable length and type	160 km, 21-mm diameter

Fig. 1 shows a block diagram of the MVC. The MVC consists of 16 low-voltage (LV) subconverter modules wired together in series at the inputs, an input plane that provides input protection, input monitoring, and converter start-up, and an output plane that provides output filtering and PWM feedback control. The MVC converts a 3 KVDC cable input to a 625 VDC output at loads of circa 3 kW. The MVC system also includes additional output modules (not shown) for control, switching, conversion, regulation, filtering, protection, and monitoring of power outputs to the internal housing payloads and to the external undersea instrumentation sites.

The MVC architecture was designed for modularity with the following building blocks: a thermally-conductive aluminum chassis with module slots, an input card with the input plane circuitry, a quad-subconverter card with four subconverters, a backplane card with monitoring, output plane, and PWM controller, one or more output cards, and power modules for internal payloads (e.g., optical amplifiers). Some of the MVC electronic modules are shown in Fig. 2.

The MVC is packaged in a 21-inch diameter primary node housing as illustrated in Fig. 3. The MVC chassis is mechanically mounted, electrically isolated, and thermally conducted to the left end cap. An optical payload is mounted in a similar fashion to the right end cap. The optical payload includes eight erbium doped fiber amplifiers (EDFAs), optical add/drop multiplexers, optical attenuators, fiber management, and redundant Gigabit Ethernet telemetry units for primary node supervisory control and monitoring. The right end cap also includes undersea cable terminations [10] to the primary and secondary power cable infrastructure as well as connections to undersea electrodes for seawater power returns.

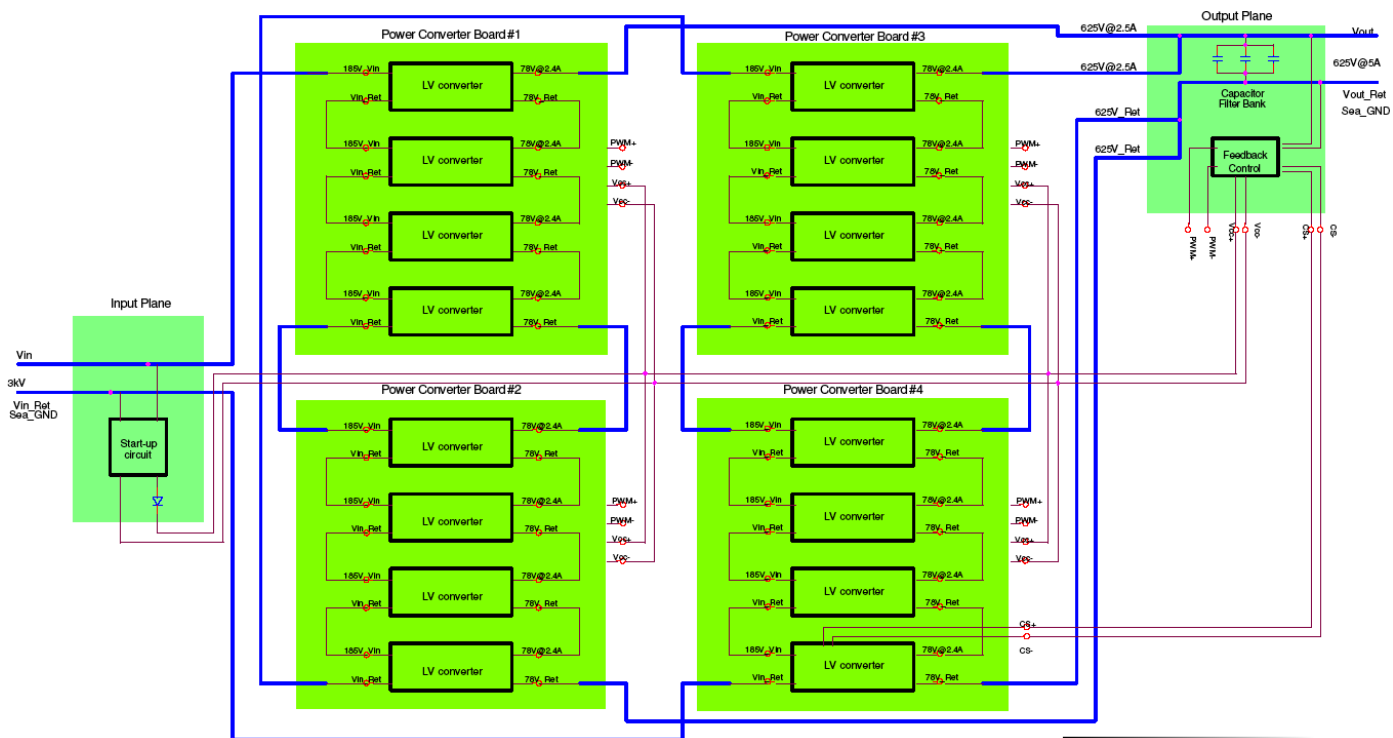


Figure 1. MVC block diagram



Figure 2. MVC modules – input card (left), quad subconverter (center), and output card (right)

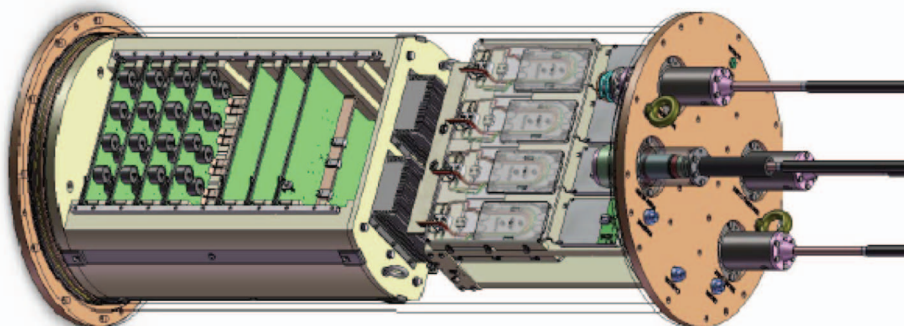


Figure 3. Primary node solid model with MVC on left and optical payload on right

III. MVC PERFORMANCE

One MVC prototype and two MVC production units were built and tested in 2007. A photograph of an MVC unit is shown in Fig. 4. As shown, the subconverter stack, which dissipates a majority of heat in the MVC, is located near the end cap for conduction cooling. Additional card slots above the subconverters hold the input and output modules. Power converters for the primary node internal payloads are mounted to the top of the chassis.

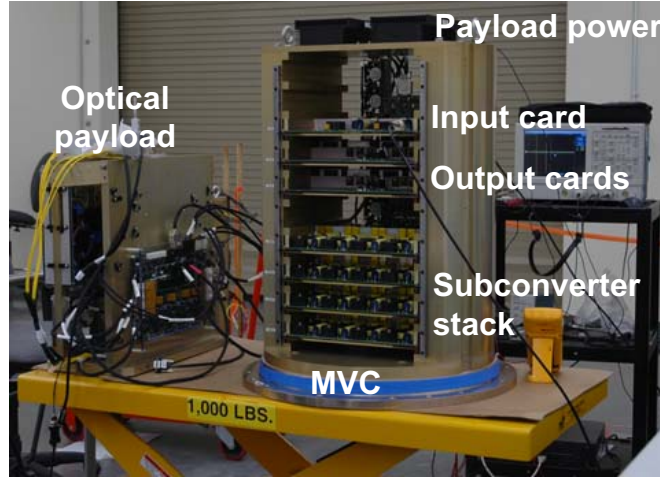


Figure 4. MVC during lab testing

The MVCs were tested with a commercial-off-the-shelf 3 kVDC power supply (a.k.a. power feed equipment or PFE) and a custom 160-km cable simulator as shown in Fig. 5. Kilowatt power loads with negative impedances and 20-km cable simulators were developed, built, and used during lab tests to simulate the secondary power infrastructure.

Power supply efficiency was measured to be approximately 90% across the load range of 2 - 3 kW. Similar efficiency was obtained across the 2.5 - 3.5 kV input range. The efficiency dropped to about 82% at light load (725 Watts).

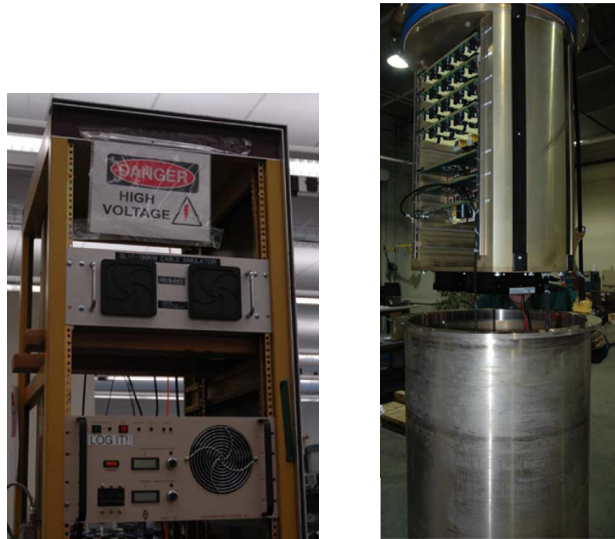


Figure 5. Rack-mount PFE and 160-km cable simulator (left); MVC and pressure housing (right)

The output voltage regulation typically varied less than ± 1 volt from no load to full load under static load conditions. The output voltage ripple was measured to be typically less than 200 mVpp across the same load range. The converter was exceptionally stable under dynamic loads, holding the output steady to within a few volts droop during 2 Amp off-on step load changes. The MVC output was also shown to hold load regulation under the failure of a subconverter module, demonstrating fault tolerance. The MVC architecture maintains operation with up to two failed subconverters for most common fault modes.

IV. UNDERSEA MVC POWER SYSTEM

Diagrams for the MVC power system are shown in Fig. 6 and 7. The system is a star configuration with a 3 kV PFE on shore, 160 km of submarine telecom cable to the primary node MVC, and three 20-km submarine cables branching to the secondary instrumentation sites. Two of the secondary branches are fed constant voltages and the third branch is fed a constant current. Each instrumentation site, the MVC site, and the shore site have wet electrodes for seawater return currents.

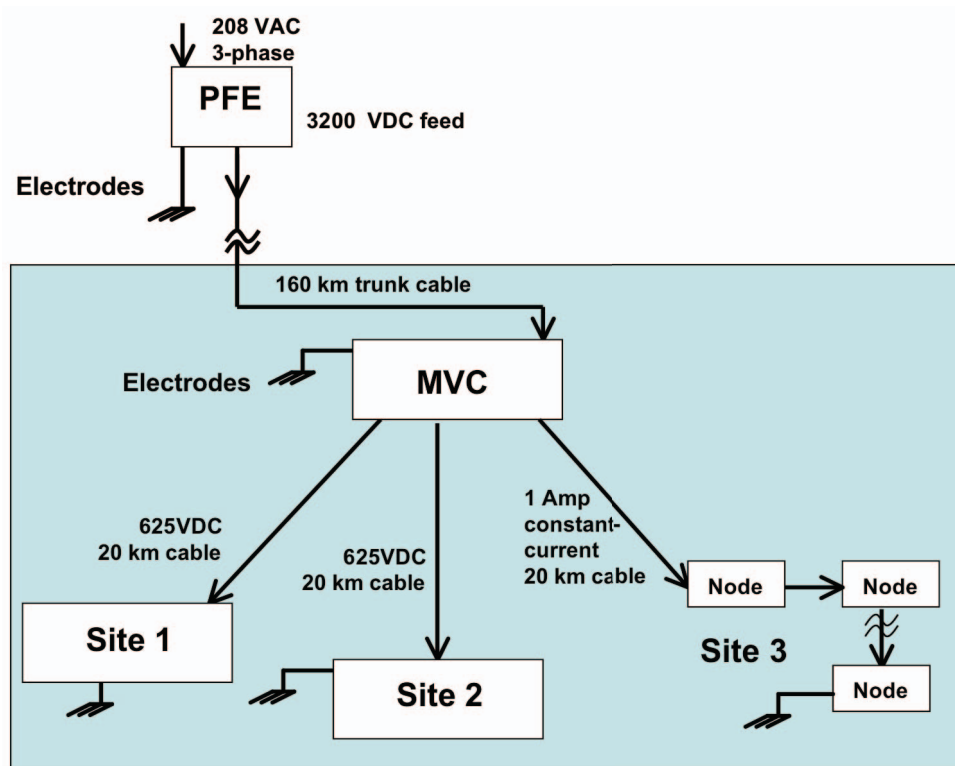


Figure 6. MVC power system diagram

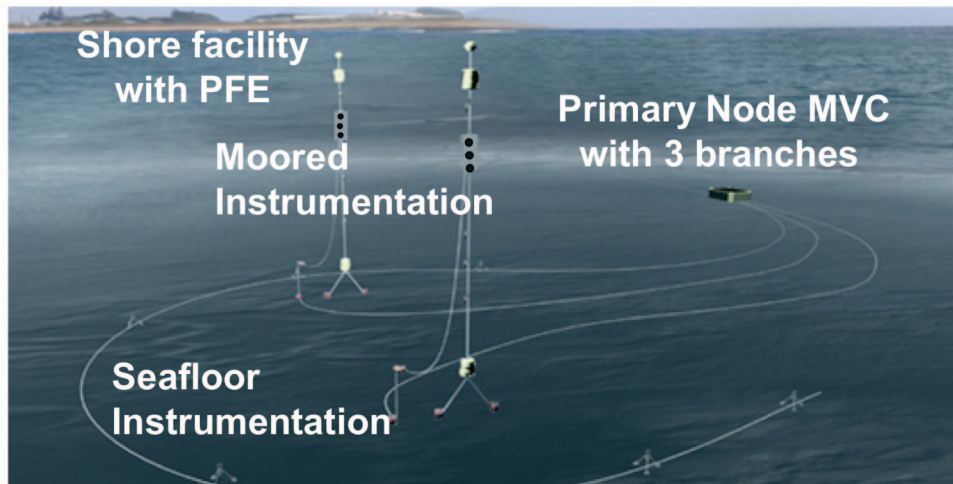


Figure 7. Example system with primary node MVC

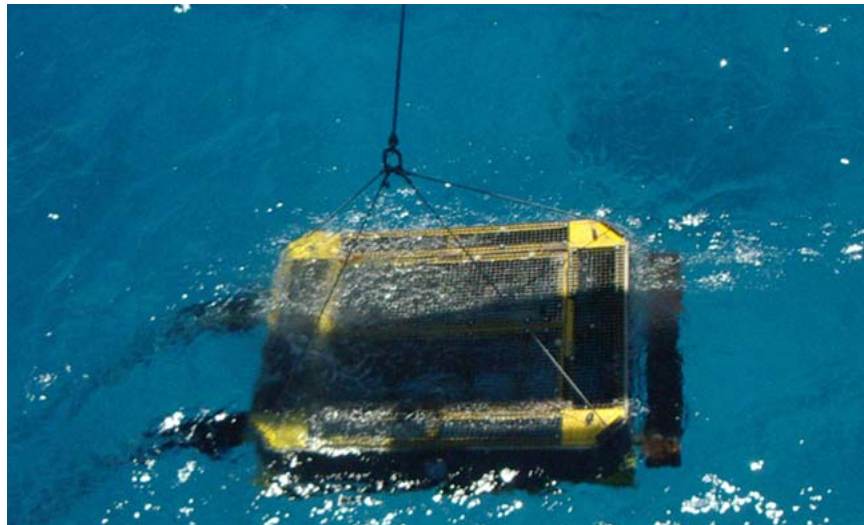


Figure 8. Subsea MVC installation in May 2008

V. SUMMARY

Modular medium voltage converters (MVCs) for undersea power systems have been at various stages of development since 2000, presenting a number of difficult engineering challenges. Unlike timing and data networks, there is little commercially available hardware that can be directly leveraged into undersea power systems for regional scale networks. This paper reports the successful undersea installation of a modular MVC in May 2008. The MVC, comprised of a stack of 16 subconverters in a modular conduction-cooled frame, provides 3kV-to-625V power conversion to a cabled undersea sensor network located more than 160 km offshore. The MVC is installed in a star topology network with secondary branches to three instrumentation sites.

We hope that this difficult but now successful milestone in undersea engineering technology will encourage the ocean observatory community and its sponsors to accelerate work and investment in regional network infrastructures. These sensor infrastructures are an important component of national science, providing much needed real-time data for globally critical topics such as ocean acidification, ocean warming, sea level changes, harmful algae blooms, carbon cycles, offshore energy production, climate prediction, disaster warning, pollution, fishery collapses, and species extinctions.

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