NEPTUNE: dc power beyond MARS

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Abstract – The modular power converter designed for the Monterey Accelerated Research System (MARS), and recently successfully tested by the Jet Propulsion Laboratory (JPL) and the University of Washington, is a significant milestone in the development of regional cabled observatories. The ability to transmit up to 10kW reliably over long distances using 10kV direct current (dc) and convert it to a more usable 400V dc locally will open up new possibilities for the science community.

For future projects covering several hundreds of kilometers and using multiple power converters, high reliability will be crucial. Some evolution of the design is therefore essential. The intention for the NEPTUNE project is to build on the MARS achievements to the point where the converter is a fully industrialized unit built to submarine telecom standards.

The JPL/MARS system includes a redundant converter available via a medium voltage switch. With relatively minor circuit changes the converter reliability can be increased so that a single converter could be more reliable than two and a switch.

I. INTRODUCTION

The architecture used on the NEPTUNE observatory was first proposed in a paper at SubOptic 2001 [1]. That paper discussed the distribution of high voltage around the observatory, and the need to convert it to a more usable voltage at the undersea science nodes.

Since then the system definition has been through a number of changes. However the basic concept is unchanged: an essential component of this approach is the dc / dc power converter. The dc / dc converter development opens up opportunities not only for NEPTUNE, but also for other future systems.

II. CONVERTER BACKGROUND

The power converter for the MARS project was designed at the Jet Propulsion Laboratory in Pasadena. It has been successfully tested there with input voltages up to 8kV and output powers up to 5.3kW [2, 3]. This MARS converter forms the foundation of the NEPTUNE development.

A number of changes have been made to the MARS converter design to improve manufacturability and provide a modular design for NEPTUNE. The MARS converter uses three different rectangular printed circuit boards (PCBs) running the length of the sea case, with each carrying either 2, 3, or 4 sub-converters. By changing to circular PCBs each with 2 sub-converters, the converter for NEPTUNE can be built in a manner more suited to normal shop floor working practices.

The MARS undersea node was designed with a redundant power converter to improve reliability. The MARS converter design can withstand a number of sub-converter failures without significant loss of performance. After studying the basic reliability of the converter and taking into account the fact that it is inherently robust it is not necessary to include the complexity and expense of using two converters per undersea node.

Using the published information [4], Alcatel Submarine Networks (ASN) have built a prototype converter with 16 sub-converters, with an input voltage of 3.2kV and output power of 2kW, and successfully tested it on a representative system test bed.

III. INDUSTRIALIZATION

The construction method of the MARS converter is appropriate when only one or two are to be built, and close engineering assistance is available. A production shop-floor environment requires a more modular approach. The NEPTUNE converter will be built on circular PCBs (approximately of 285mm diameter), each carrying two sub-converters, allowing sub-converters to be tested in pairs. The PCB layout will be arranged such that boards can face each other with high and low components interleaving to allow optimum volume efficiency.

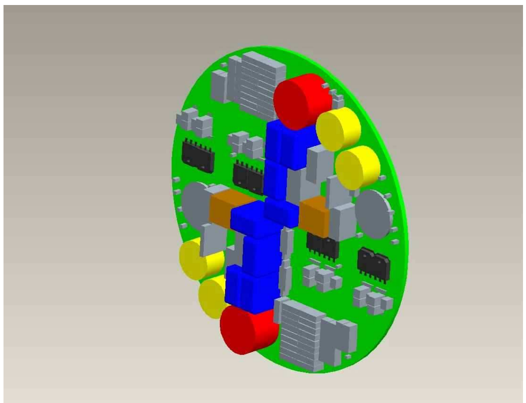

Fig 1 lay out of 2 sub-converter PCB

Electrically, the full converter will have 48 sub-converters arranged as six parallel groups each of eight series connected sub converters. The convenient next step for assembly is to assemble 4 PCBs (i.e. 8 sub converters) together. This module will then tested with a control loop at 1600V input and 400V output.

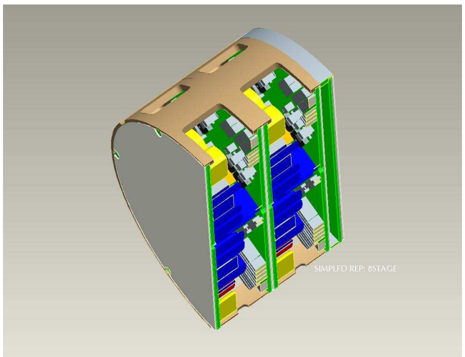

Fig 2 construction of 8 sub-converter module

Six of these 8-converter modules would then be brought together to form the full converter of 24 PCBs of 48 sub-converters, assembled into the pressure vessel.

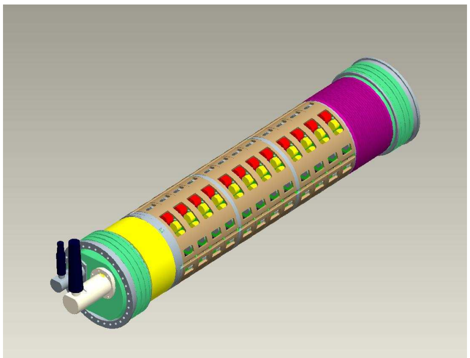

Fig 3 construction of full converter

IV. RELIABILITY

Reliability analysis of the converter has shown that it is difficult to justify the complexity and expense of putting more than one converter in a science node. The basic sub-converter has a reliability of 456FITs [See Note 1]. Of each series group of 8 sub-converters it is possible to have as many as 4 fail before the overall performance is degraded. This inherent redundancy greatly increases the overall converter reliability.

However, there would be little advantage in having a very reliable converter without a similarly reliable control system. A single controller represents a single point failure, and limits the overall reliability. The MARS converter overcame this problem by having two converters each with its own controller. The NEPTUNE converter will have up to 6 controllers. This number will allow for easier testing of groups of 8 sub-converters during manufacture, and gives a good overall converter reliability estimate of 807FITs.

It is important to prevent the situation of more than one converter being active at any one time. Voting logic is under development to achieve this objective.

An essential part of the reliability philosophy is that a single sub-converter failure should not cause the failure of the complete converter. A failure of a switching FET on the primary side of the sub-converter would normally be a short circuit, allowing the remaining 47 sub-converter to continue working. On the rare occasion that a FET might fail open circuit, the whole converter would fail to operate. To mitigate the effect of this possibility an additional circuit has been introduced across the input of each sub-converter.

To avoid the loss of the complete converter by an open circuit failure of an output component, a bypass diode has been added on the output of each stage to prevent this.

V.THERMAL MODELING

Tests on the 16 stage prototype converter have shown that efficiencies in the region of 90% can be expected. On a full 48 stage converter this represents a loss of 1kW. Thermal modeling has shown that the surface temperature of the semiconductors will not rise above 40^{o}C.

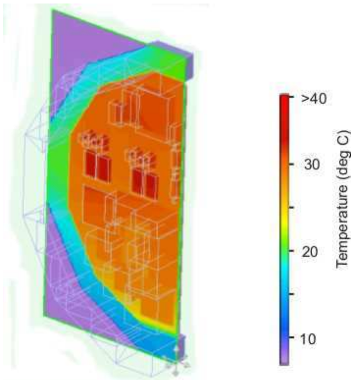

Fig4 Result of thermal model

VI. FIRST PROTOTYPE

The first prototype is a bench-top model with 16 sub-converters arranged as two parallel groups of eight in series. It has a maximum input of 3.2kV and maximum output of 2.8kW. The sub-converters are built on a 200mm diameter PCBs and then mounted on a cylindrical frame with the control board at one end.

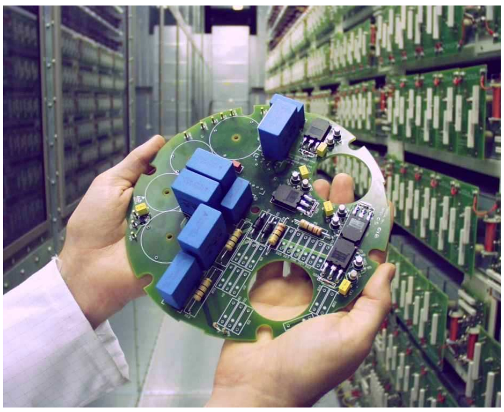

Fig 5 200mm diameter sub-converter

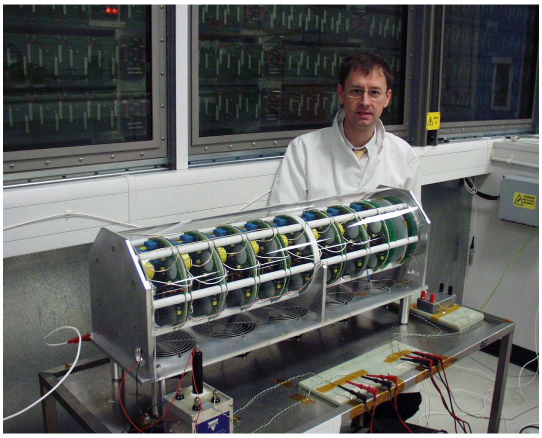

Fig 6. 16 stage converter in the Test Bed

When working at 10kV the converter will be housed in a pressure vessel filled with Fluorinert, to provide cooling and insulation. For the prototype, air insulation is sufficient, with cooling by fans as required.

The purpose of this model was to learn as much as possible about the technology by testing it within a simulated system before building a full 10kV prototype. The converter has been tested with a commercial Power Feed Equipment, 600km of lumped parameter cable simulator containing simulated repeaters, and an under sea Branching Unit (BU), see Figure 7.

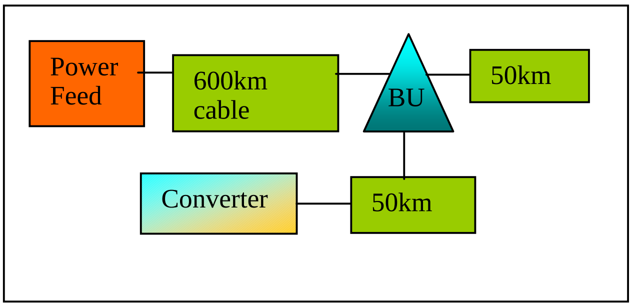

Fig 7 test setup

The following experimental results show the efficiency is about 90%. The Power Feed was set to 3.2kV. The lower input voltage is due to volt drop along the cable.

Vin	2553V
Iin	851mA
Pin	2172W
Vout	405.8V
Iout	4.9A
Pout	1988W
Efficiency	91.5%

Table 1 2kw output

Vin	2815V
Iin	420mA
Pin	1182W
Vout	415.8V
Iout	2.52A
Pout	1047W
Efficiency	88.5%

Table 2 1kW output

VII. CONCLUSION

The development of the first prototype NEPTUNE converter has proceeded as far as a first 16-stage prototype. The overall converter architecture is generally the same as that developed at JPL for the MARS system. Only a single converter will be used per node, but it will include multiple controllers to provide redundancy and improve reliability. The PCB configuration is based on a circular board, and converter is laid out in a modular fashion to aid manufacturability and future possible design variations.

ASN are now proceeding to design and test a full scale 10kW prototype, before finalizing on the industrialized high reliability unit required for deployment on NEPTUNE and other cabled observatories.

ACKNOWLEDGMENT

All those working on the NEPTUNE project at ASN would like to thank the team at JPL for the excellent work on the MARS converter. Experience with other converter developments at similar voltages and powers suggest that the early stages of development are the most difficult. The very few problems encountered by ASN in realizing the first NEPTUNE prototype is a testament to the high standard of work completed by the JPL team..

The authors would also like to acknowledge the many helpful discussions with the MARS / NEPTUNE power group, the Advanced Physics Lab at the University of Washington and in particular with Vatché Vorpérian from JPL.

Note 1

1 FIT = 1 failure in 10^9 hours = MTBF 114,000 years
465 FITs = MTBF 245 years
807 FITs = MTBF 141 years

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Ref2: Vatche Vorperian, "Architecture for a High-to-Medium-Voltage Power Converter," NASA Tech brief for NTR-40364.

Ref3: Vatche Vorperian "Test results of the 10kV-to-400V dc-to-dc converter for the MARS project," JPL Document No. D-33812, December 26, 2005.

Ref4: http://neptunepower.apl.washington.edu/documentation/documentation.html