Power Systems for Ocean Regional Cabled Observatories

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***Abstract* - Development of power systems is the most challenging technical issue in the design of ocean regional cabled observatories. ARENA and NEPTUNE are two ocean regional cabled observatory networks with aims that are at least broadly similar. Yet the two designs are quite different in detail. This paper outlines the both systems and explores the reasons for the divergence of design, and shows that it arose because of differences in the priority of requirements.**

I. INTRODUCTION

Regional cabled observatories are expected to bring a breakthrough to many underwater research areas, and some related projects have been initiated or proposed all over the world.

Development of power systems is the most challenging technical issue in realizing ocean regional cabled observatories (RCOs). There are no similar power systems on which to base designs. RCO power systems are quite different from those of underwater telecommunication cable systems. This difference is caused by the difference in the network architecture and the magnitude of the required power. They are also quite different from terrestrial power systems. Thus the power systems must be developed from the ground up.

ARENA [1] and NEPTUNE [2] are two sub-sea networks proposed or initiated in Japan (ARENA) and in the USA and Canada (NEPTUNE). The aims of these two networks are at least broadly similar. Although both networks will use under-water telecommunication cables which have only one conductor in the cable, the two designs are quite different in detail. NEPTUNE adopted a constant voltage power feeding system, whereas ARENA adopted a constant current power feeding system. The constant voltage power feeding systems have the advantage that it is easy to branch the power cable. On the other hand, constant current power feeding systems are inherently robust against cable shunt faults.

This paper outlines both power systems and explores the reasons for the divergence of design, and shows that it arose because of differences in the priority of requirements that each network was designed to satisfy.

II. REQUIREMENTS

In a well-ordered world, no hardware would be fabricated, no software would be written, without first a well-crafted set of Requirements. These Requirements would spell out *what* the project was supposed to accomplish, without in the least describing *how* the goals were to be accomplished.

This is not a particularly well-ordered world, however, and many projects are well under way before the Requirements are finalized. In truth, the Requirements of many works of a scientific nature are never well defined. The participants just *know*, or think they know, what has to be done. Certainly in the case of the sub-sea observatories known as ARENA and NEPTUNE, the Requirements were at best in rudimentary form as the projects got under way.

As far as the power subsystems of these two projects were concerned, some Project-level Requirements *were* defined for each observatory. For ARENA, the challenge was principally to continue operation if not during then immediately following a cable fault. This requirement supports the need to monitor seismic activity even if that activity results in a cable fault. NEPTUNE's charge, on the other hand, was to bring as much power as possible to the sub-sea science nodes, using a conventional cable of the telecommunication type. The assumption here was that more power would enable a wider variety of science.

These, of course, were not the only Requirements. There were other Requirements on the power subsystem, and Requirements that applied to other aspects of the observatories, such as the communication system. Ultimately, all these technical Requirements derive from the Science Requirements, a set of Requirements that define the scientific purpose of the observatory. The Science Requirements, in turn, derive from the Requirements that express the wishes of the sponsor. Thus, Requirements can be organized into different Levels addressing the design or operation problem at different scales. The Table below gives some examples.

TABLE I   Requirements Levels

Level	Name of Level	Example
1	Sponsor	Build an observatory for science *x-y-x* part of the ocean
2	Science	Provide infrastructure to acquire water column data
3	System	Provide power and communicatio capability
4	Subsystem	Provide power at 48 V dc
5	Component	Provide switching devices

The various Levels are explained as follows:

TABLE II Responsibility Matrix

Level	External Stakeholders, Sponsors	Project	System Engineering	Subsystem
1	approve	recommends	is consulted	
2	is informed	approve	recommends	is consulted
3		is informed	approves	recommends
4			is informed	approve
5				approve

1. Requirement comes from major stakeholders, government, multiple observatory partners, funding agencies and sponsors.
2. Requirement is at the Project level, likely something driven by science needs.
3. This is the system level. A system-level Requirement would involve more than one location, or more than one kind of science, or impact more than one subsystem.
4. This is the subsystem level, and has no impact outside the subsystem.
5. This is the component level. The effect of a trade-off at this level may be limited to a minor part of a subsystem.

Participants at various levels in the hierarchy are differently involved in the approval process for Requirements, and in the trade-off process for solutions that implement Requirements, as indicated in Table II.

Requirements are sometimes adopted iteratively. For example, a science requirement may be generated at the Project level, and sponsors may be informed about it. However, it is likely that the system engineers would be involved in the definition of the Requirement, and even the subsystem may provide input that results in a modification of the original Requirement.

Interestingly, the high-level requirements on the two schemes led to some similarities and some differences from the beginning. Both observatories would be implemented by the use of standard telecom cable, providing a power and telecommunications infrastructure connecting to shore. Both would enable science to be done at a limited number of locations of scientific interest. Both would aim at a long life for the sub-sea equipment. But while both observatories were to be capable of supporting many kinds of observation, robustness would have a higher priority in ARENA, whereas NEPTUNE concentrated on providing a high-power infrastructure for general application.

III. ARENA POWER SYSTEM

Although ARENA has multidisciplinary scientific objectives, as does NEPTUNE, seismology has priority because Japan is located near plate boundaries where catastrophic earthquakes occur periodically. That means the cabled observation network should continue working and monitoring those rare earthquakes even if some portion of the network is damaged by a landslide or a tsunami. This requirement affects the basic design of the power system[3].

ARENA was planned with two trunk cables laid one on each side of the plate boundaries. This results in a need for the underwater devices to be deployed and maintained up to 6,000 meters in depth. Consequently, the size and the weight of the underwater devices are to be restricted due to handling capacity of cable-ship or related work vessels.

A. Selection of powering method

In the ARENA feasibility study [4], we compared three methods of powering the system. They were (1) Constant current (CC) power-feed system, (2) Constant voltage (CV) power-feed system, and (3) Hybrid power-feed system that consists of both CV power feed subsystem and CC power-feed subsystem.

As a result of the feasibility study, constant current power feeding was selected as the most promising option. It has many advantages, such as

(a) It is robust against cable faults, meaning that operation can continue by the simple expedient of adjusting the voltages at the power feed. It can continue operation except for possible short interruptions to prevent damages due to surge currents.
(b) It is easy to locate cable faults, as primary power lines are isolated from sea water.
(c) The electric power circuits in the underwater repeaters are simple and easy to isolate from the sea ground.
(d) Its basic technology is field-proven as it is widely used in the submarine telecommunication cable systems.

There are disadvantages in the constant current power feeding system. It is not easy to branch electric power into two lines, although power-branching is needed to efficiently deploy sensors two-dimensionally. On the other hand it would be simple for a constant voltage system. Further, most loads at science nodes require constant voltage, so there is the need to provide some sort of converter. There would be conversion efficiency issues.

One challenge of the constant-current scheme is to develop a small and reliable device which branches an input current into two (or more) cables at a branching location. (Of course, if the input current and the output currents are equal, the voltage at the outputs must be lower than that at the input, or the energy conservation law is broken.) We call the device a *current-to-current converter*, and the node at that location a Power Branching Unit (PBU).

It is also a challenge to develop for the loads a converter of high efficiency that generates a constant voltage source from a constant current. While such a device has been discussed by ocean scientists interested in re-use of existing cables, there are not known to be any practical implementations.

The ARENA committee proposed an engineering model of the network shown in Fig. 1 to enable quantitative analysis and design. This model has four landing stations that feed electric power to the network, and eight power branching units that branch the incoming constant current. The trunk cable of 400km in length in Fig. 1 is powered from the two PBUs at the both ends, with a current value on the order of a few amperes. The average

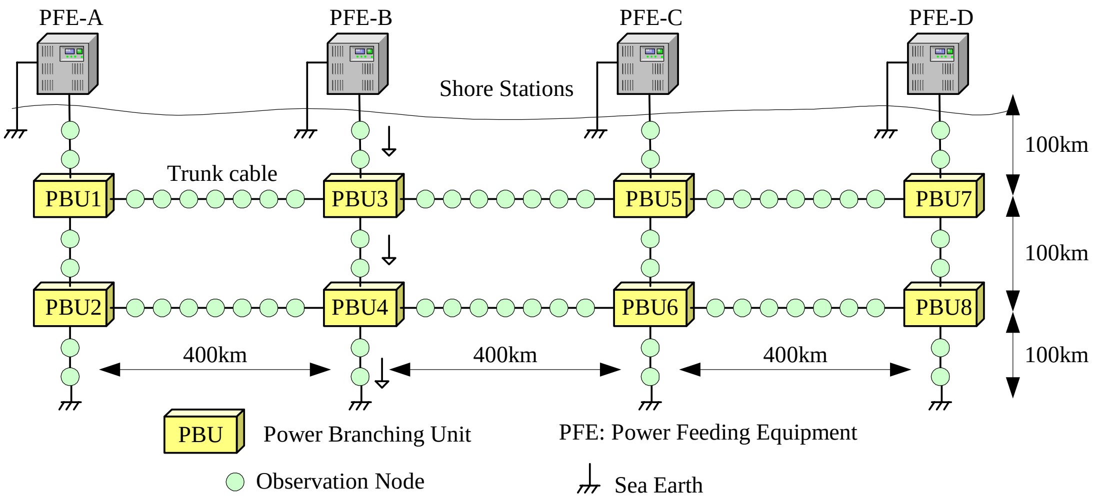

Fig. 1 Engineering model of the power feeding network of ARENA

power consumption of observation nodes is estimated to be about 400 watts

Even if a cable shunt fault occurs near the PBU, observation nodes in the trunk cable are required to continue operating. Therefore, one PBU is required to be able to feed power to the cable of 400km, which corresponds to an electric power supply of 3.9kW including the voltage drop of the cable.

B. Current-to-current converter

In the feasibility study, a new current-to-current converter was proposed that enabled branching a constant current. Fig. 2 shows the proposed basic circuit of the current-to-current converter.

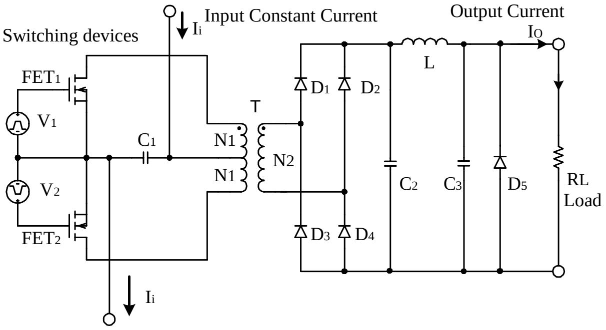

Fig.2 Basic concept of Current to Current Converter

The input dc constant current is switched with switching devices FET1 and FET2, converted into alternative current, and put into the transformer. The output of the transformer is rectified and filtered to make another dc constant current. The output current is determined only by the input current and the winding number ratio of the transformer. As this basic circuit is very simple, high reliability and high conversion efficiency can be expected.

Fig. 3 shows a typical configuration of the PBU. The PBU is composed of several current-to-current converters, including spare ones. The input and the output of all the converters are connected in series in order to increase the total output power. In Fig. 3, converter-3 is a spare and its input is shunted by the switch SW-3. The input current flows in SW-3, and the output current from other converters flows in the diode D3. When one of the working converters fails, its input will be shunted with the corresponding switch. Opening SW3 will activate the spare converter.

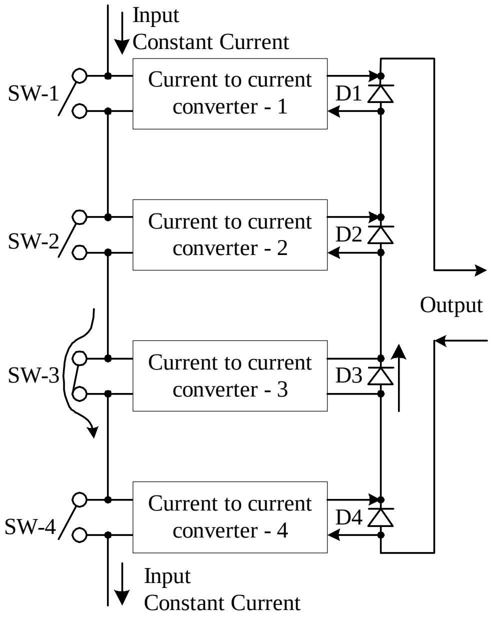

Fig.3 Typical configuration of PBU

Asakawa *et al* [5] successfully developed a prototype converter that has an output power of 650W and efficiency of more than 90%. In order to realize a PBU with output power of 3.9kW, six converters and one spare converter should be connected serially. As PBUs practically limits the power supplied to branched segments, high efficiency and small size are important.

C. Science Node Converter

A simple way to realize the converter which generates a constant voltage source from a constant current is to use a shunt regulator. A Zener diode can be used for a shunt regulator, having simplicity and high reliability. This technique is used in submarine telecommunication cable system repeaters. Unfortunately, the efficiency is quite low. In the Japanese VENUS project [6], a science node converter was realized by a combination of a current-to-current converter and an active shunt regulator (Fig. 4).

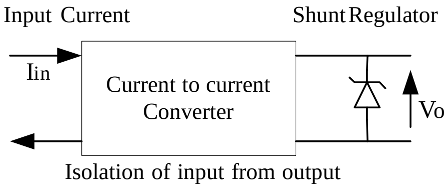

Fig. 4 Science mode converter

This shunt regulator approach has low efficiency at low load. Recently, a new way of generating a constant voltage source from a constant current was proposed in the ARENA committee. Good conversion efficiency is expected for this method. It will be examined and will be reported in the near future. Note that a conversion system such as this will also be generally useful for scientific re-use of optical submarine telecommunication cable systems.

IV. NEPTUNE POWER SYSTEM

At an early meeting of the NEPTUNE collaborators, the question was asked whether a series system or a parallel system was capable of delivering more power. Since all land power systems since the time of Edison have been parallel, the assumption must be that the answer is *parallel*, but in truth none of the then participants could think of why this should be. Perhaps the utility world had opted for a parallel system simply because of the Christmas-tree light problem: a single bulb failure could make a whole string go dark.

Eventually, a small study was done (see http://neptunepower.apl.washington.edu for a copy of the report, under *Documents / System_Aspects / System_Wide*) that showed that a parallel system is indeed capable of delivering more power than a series one. In retrospect, this should perhaps have been obvious, as the losses in a series system are independent of the load served, whereas they increase with the load in a parallel scheme. The efficiency is always better, therefore, in a parallel system. Strange as it seems, even this conclusion was not without its critics, who pointed out that the study's conclusion was based on the *maximum* power that could be delivered, and that in a parallel scheme the point of maximum power is inherently unstable. Nevertheless, the point was finally accepted, and the NEPTUNE system was based on a parallel architecture.

A. Features of powering method

The NEPTUNE power system would be based on a Constant Voltage delivery scheme. It has none of the advantages claimed for the constant-current scheme:

(a) it is *not* robust against cable faults, requiring additional equipment to clear such faults before operation can resume,
(b) it is easy to locate cable faults, *but* operation must be interrupted,
(c) standard underwater repeaters may *not* be feasible in view of the current variations they will experience during system operation,
(d) it is *not* used at all in the submarine telecommunication cable systems,
(e) its technology is *not* field-proven, and
(f) any load on the system requires the use of either a return cable or a sea-ground for the return current. (For cost reasons, NEPTUNE uses a seawater return.)

However, the constant voltage approach does have some advantages:

(a) branching to create a network of cable is a relatively trivial matter
(b) the amount of power that can be delivered to a science location is much higher than in a constant current scheme
(c) it is a straightforward matter to provide power at constant voltage to the loads.

The power delivery system that evolved was a network of cables serving around 30 or 40 science nodes, see Fig. 5, with power being fed by two shore stations, one in Canada and one in the US [7]. Since the power system (like all power systems) is inherently nonlinear, it is hard to specify a rating. However, it is possible to get an impression. Each science node is to be equipped with a converter rated at 10 kW. Load-flow calculations show that all the nodes in the system could be fed with around 6 kW simultaneously, if both shore stations are operating. If the converter could be overloaded, as much as 16 kW could be delivered to the most distant node while 1 kW was delivered to every other node.

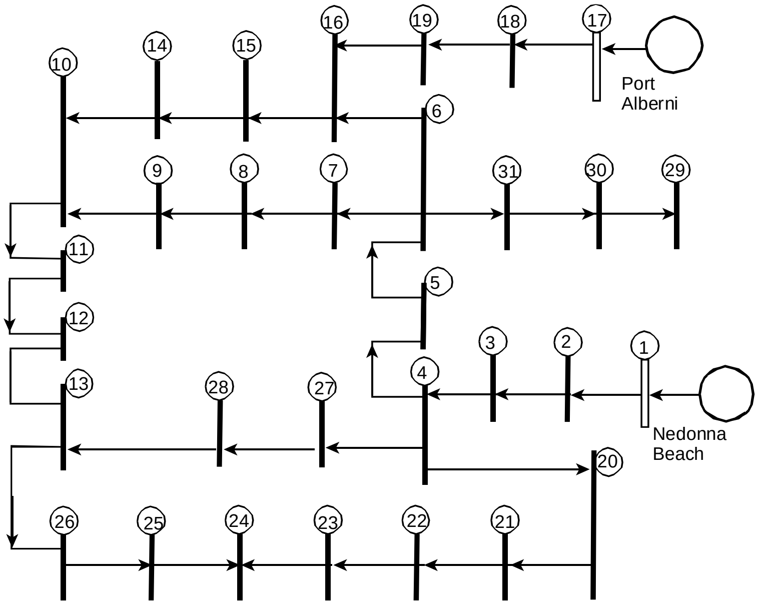

Fig. 5. NEPTUNE one-line diagram

In Fig. 5, the arrows show the direction of current flow, assuming all loads are equal. As it happens, there is no current between nodes 12 and 13.

B. System protection

The word *protection* has a different meaning to a communications engineer and a power engineer. To a communication engineer, protection is the provision of an alternative path for information, to be activated in the event of a fault. To a power engineer, protection means the detection of a fault, and the removal of the faulted circuit. It is in this latter sense that we use the term here.

In a parallel system such as NEPTUNE, a cable fault will short the conductor to seawater, and the voltage in the delivery network will collapse. (Just how widespread the collapse would be would depend on the details of the network and the location of the fault.) Damage is limited by arranging for the shore station to go into a current-limit mode, and reduce the voltage.

In order to resume operation, the fault must be isolated. Isolation requires two things: the location of the fault must be known, and some kind of circuit interrupter must be in place to open the path to the fault. For both of these activities, the appropriate *resolution* is the node spacing. There is no benefit to being able to clear a fault and energize a cable that does *not* include a node, and there is an obvious problem if clearing a fault necessarily means isolating one or more nodes. This being the case, the NEPTUNE protection system is designed to isolate faulted cables between nodes. Fig. 6 shows the arrangement.

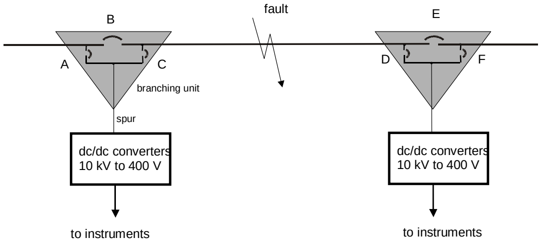

Figure 6. Fault clearing in a parallel system

In the event of a cable fault as shown, the system will operate so as to open the switches at B, C, D and E before restoring the system voltage. All science nodes are still operable. Note that the switches are not *circuit breakers*. No attempt is made to clear the fault while a large current is flowing (such a current can result from the discharge of the cable capacitance), or while the shore station is not in current-limit mode. This approach extends the life of the switching devices without requiring complex current-commutating circuitry.

By powering the circuitry for system protection from a separate high-reliability scheme inside the branching unit, dependence on the node power system is eliminated. The result is a robust backbone whose operation is independent of the science nodes[8]. This kind of design maximizes the overall system availability.

C. Science node converter

As the design grew, it became evident that the parallel delivery system would require the development of a new kind of dc/dc converter: one that would take the incoming voltage (around 10 kV) and deliver a more useable level to the science node under the sea. This converter had to meet two challenging Requirements: it had to be small enough to fit into a modest-size pressure case, and it had to be reliable enough that the sponsor would not be required to fund a large number of ship visits for repairs[9]. In essence, both of these are Level 1 Requirements, directly affecting the sponsor.

A modular converter was designed that handles the relatively large input voltage by using many stages in series on the input [10]. Because each module is small (200 W), it operates at a relatively high frequency (50 kHz), to minimize component size. The individual converters are based on the use of a 1:1 transformer. The input voltage per module (between 100 and 200 V) is between two and four times the output voltage (fixed at 50 V). There are 48 such modules in a converter, with the inputs in series and the outputs in a series-parallel arrangement to deliver 400 V. This high voltage allows science users to locate their loads some km away from the node itself. Users that require a lower voltage are fed via additional down-converters [11].

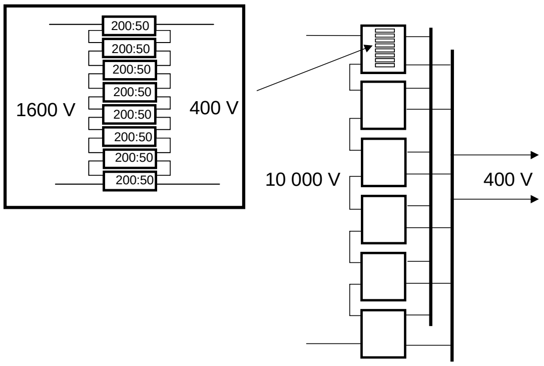

Figure 7 Block diagram of 10 kV to 400 V dc/dc converter

There are several challenges in the design of such a converter: apart from the need to control the electric field associated with the high input voltage, there is the need to ensure that the input voltage across each stage is the same, and the output current is shared by all stages. When this approach was first proposed (in 2001), some of our colleagues were of the opinion that these problems could not be stably solved.

Since then we have shown that one key to the success of the design is the use of only one PWM controller, and only one feedback signal representing the output voltage. At the time of writing (September 2004), we have demonstrated the stable operation of two blocks of 8 converters, with an input voltage of 3.2 kV. Extrapolation from 3.2 kV to 10 kV is not viewed as particularly high risk. (Interestingly, the system that has been demonstrated in the laboratory would meet the requirements of the Canadian VENUS scheme, where an input voltage of 3 kV has been proposed. For an overview of this project, see “VENUS, Future Science on a Coastal Mid-Depth Observatory” at http://www.neptunecanada.ca/reports/index.html)

The converter is designed to operate in a liquid dielectric. This liquid (for example, Fluorinert FC72) has a good electrical withstand, and excellent convection properties. Tests done on a model of the converter indicate that even at full power, the temperature of the switching transistor junctions will be less than 38 C. Such cool operation is expected to contribute to meeting the Level 1 requirement for a long life with low maintenance needs.

V. COMPARISON OF POWER SYSTEMS

Now that we have explored the designs of the power systems for the two observatories, we can compare them. In TABLE III we look at the similarities and differences in some detail.

TABLE III Comparison of two power systems

	ARENA	NEPTUNE
Normal operation		
Power delivered	3.9 kW per any one branched cable segment, limited by PBUs. Maximum power from each shore station ~ 20 kW limited by cable withstand voltage	Few kW per node, 10 kW max. Total power from each shore station ~ 100 kW, limited by stability issues
Branching	Requires current-to-current converter	Requires just a connection
Faulted operation		
Shunt fault (rare)	Shore stations automatically adjust voltages to keep current unaffected	Require detection, location and isolation before operation can resume. Cost aspects imply that NEPTUNE may *not* implement the ability to disconnect at a branch
Open fault (extremely rare)	Most likely causes loss of service to the corresponding cable segment	May reduce overall power delivery capability
Recovery time (shunt)	Virtually instantaneous	Minutes, possibly tens of minutes
Fault location	Can be done during system operation using conventional methods such as resistance measurement and monitoring of nodes	Can be done using conventional methods such as resistance measurement, but requires science operations to stop
Development required	Current-to-current converter Current-to-voltage converter	MV-to-LV converter Fault protection scheme
Operations	Increased load at a node causes increased volt-drop at that location. Depending on power level and network configuration, the cable voltage rating is thus the factor that limits power capability	Increased load at a node causes increased current into that location. Depending on power level and network configuration, this could affect the network stability via voltage collapse

VI. CONCLUSION

ARENA and NEPTUNE are two scientific sub-sea networks with aims that are at least broadly similar. Yet the two designs are quite different in detail, one being based on a series power delivery architecture and the other on a parallel approach. The designs differ because of differences in the Requirements levied on the two networks: one had to operate even in the event of a major earthquake and a concomitant cable fault; the power delivered could be limited by PBUs: the other was permitted to shut down and restart following a cable fault; but a high power level was required to be delivered. There is no *right* or *wrong* about this; each observatory meets the requirements set for it.

The work done on the two projects reported here promises to be beneficial to other ocean observing projects. In particular, the new hardware developed, the current-to-current and current-to-voltage converters, and the modular dc/dc converter, hold out the promise of simple adoption on other networks, whether they are new or will involve the re-use of existing cables.

The choice of powering systems for future cabled ocean observatories will evidently not be restricted by the capability of the electronics.

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