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Development of a direct current power system for a multi-node cabled ocean observatory system*

Yan-hu CHEN, Can-jun YANG‡, De-jun LI, Bo JIN, Ying CHEN

(*State Key Lab of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*)

E-mail: {yanhuchen, ycj, Li_dejun, bjin, ychen}@zju.edu.cn

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Abstract: Due to the shortage of suitable research methods for real-time and long-term observation of oceans, an innovative approach that can provide abundant power and wide bandwidth is being developed worldwide for undersea instruments. In this paper, we develop a direct current (DC) power system which is applied to a multi-node cabled ocean observatory system named ZERO (Zhejiang University Experimental and Research Observatory). The system addresses significant issues ranging from terrestrial facility to subsea infrastructure, and focuses on using appropriate methods to deal with several key challenges, including delivery, conversion, distribution, and management of power, and heat dissipation in pressure vessels. A basic laboratory platform consisting of a shore station, a primary node in a water tank, and a secondary node in a deep-sea simulation chamber under 42 MPa pressure was built and fully tested. An improved secondary node was deployed in Monterey Bay in California for a deep-sea trial. An 11-day laboratory test and a half-year sea trial proved that the DC power system based on our proposed methods is viable for the underwater multi-node observatory system.

Key words: Cabled ocean observatory system, DC power system, Heat dissipation, Deep sea
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1 Introduction

Oceans make up over 70% of the surface of the Earth and are central to the global environment and ecological systems. Thus, understanding the complex interactions between the atmosphere and oceans is critical to human habitability. However, conditions in the ocean, especially in the sea, hinder human's understanding processes. Current approaches used to study the ocean are usually based on ships, satellites, buoys, or off-line science instruments. Many fascinating processes or phenomena, such as erupting submarine volcanoes, thriving lives, marine and mammal living patterns, tsunamis, and earthquakes, have an episodic or long-term fashion. Thus, an innovative approach that enables remote operation, real-time observation, and long-term service is necessary for understanding interactive relationships in the ocean. At the beginning of the present century, the construction of innovative facilities called cabled ocean observatories was initiated and has been a hot topic (Clark and Sekino, 2001; Austin *et al.*, 2002; Petitt *et al.*, 2002; Dewey and Tunnicliffe, 2003; Chave *et al.*, 2004; Fairly, 2005; Favali and Beranzoli, 2006; Barnes *et al.*, 2007; Barnes and Tunnicliffe, 2008; Jenkyns, 2010; Aguzzi *et al.*, 2011a). Innovative platforms have been built for ocean science research (Sosik *et al.*, 2003; Aguzzi *et al.*, 2011b; Matabos *et al.*, 2011). By netting all independent subsea instruments to the terrestrial power grid and global Internet via subsea optical-electrical cables and special subsea mechanical-electrical facilities, an unprecedented amount of power and a wide bandwidth can be provided to access and control netted instruments. The world's first regional cabled ocean observatory system named NEPTUNE is currently

‡ Corresponding author
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being built under the joint effort of Canada and USA, and the Canadian contribution was first mounted in December 2009 (Barnes *et al.*, 2007; Jenkyns, 2010). A new mechatronic facility that features the functions of power conversion and distribution, data transmission, fault detection, and isolation, is being developed in the laboratory, and the lab prototype Zhejiang University Experimental and Research Observatory (ZERO) has been built for preparatory study. The facility is expected to yield a cabled ocean observatory system that is flexible for expansion, contains multiple nodes, and is suitable for abyssal depth (4000 m) in China seas.

In this paper, we present a power system applied to such a multi-node observatory system. First, an overview of the structure of the proposed networking system, including the power delivery structure, is introduced, along with the key challenges faced in the current project. Then the corresponding methods to deal with the challenges, especially those pertaining to power delivery, conversion, distribution, management, and heat dissipation, are discussed. To validate the construction concept and solution methods, a prototype was built in the laboratory, and results of its tank test and sea trial are shown.

2 Overview of the networked observatory system

The structure of the proposed networked observatory system is shown in Fig. 1, together with the power delivery and communications mechanisms. The power feeding equipment (PFE) fixed at the shore station is directly connected to the terrestrial power grid. Meanwhile, a data management system installed at the shore station accesses the Internet. A subsea optical-electrical composite cable beginning from the shore station lies on the seafloor and branches into many parts via branching units. Copper conductors and optical fibers are branched. A main netting node or the primary node (PN) addresses the terminal of each branch. Using waterproof connectors or contactless connectors (Li *et al.*, 2010), every PN can provide abundant power and wide bandwidth for science instruments (SIs) through standard science ports. Further, a cascading port is provided at each PN to extend a secondary node (SN), which significantly expands the observation area. Similar to the PN, an SN has several external science ports. At all nodes, data can be packaged and accessed via standard Ethernet protocols and transmitted through optical fibers between the node and shore station. Long-term serial power and wide bandwidth real-time communication are possible for subsea instruments, because power is delivered by copper conductors and data is transmitted through optical fibers.

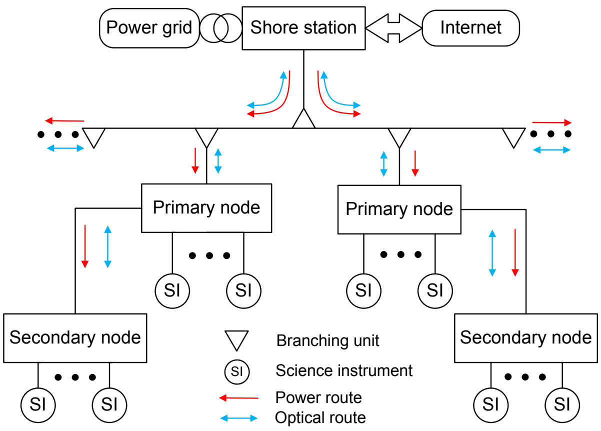


Fig. 1 Structure of the networked observatory system

Challenges exist when developing the power system because there are many differences between oceanic and terrestrial systems. These challenges include: (1) The delivery of power to the seafloor is difficult as most current electrical power transmission methods require large and complex equipment, which is not suitable for applications in the deep sea; (2) All electric components must be housed inside water-repellent and pressure-resistant vessels; (3) The limited inner space is a challenge for heat dissipation during long-term work; and (4) The cost for maintenance of a subsea facility is always high, so reliability becomes the first consideration for the current system.

Several key technologies to solve these problems are introduced and detailed below.

3 Methods of power delivery, conversion, distribution, management, and heat dissipation

3.1 Power delivery method

The terrestrial power grid is based on a parallel structure, as it can deliver more power to a subsea power system compared with a serial one. However, the grid in a subsea system is not identical to that in a terrestrial system. For the current system, with the power terminal users underwater, the power conversion equipment in subsea systems should be of the smallest possible size. Traditional methods are unacceptable here. We select a direct current (DC) high voltage to power the whole system due to the following reasons (Kirkham *et al.*, 2001; Kojima *et al.*, 2004; Howe *et al.*, 2002; 2006): (1) High voltage delivery is necessary for reducing cable loss. (2) DC voltage reducing devices are much smaller than alternating current (AC) voltage reducing devices, and a smaller device is preferable in the deep sea. In addition, when AC voltage is used to transmit power, the parasitic inductance and capacitance of long cables may induce additional problems, such as decreased system stability. (3) In contract to the AC system which has three or four conductors, two or even one conductor with seawater is enough as the current return path in the DC system. Applying a DC system can reduce the cost of constructing an underwater power system and fault risks on cables. Based on these considerations, public AC power was converted into DC power and kept at a reasonable level in the shore station. Voltage-reducing devices at corresponding levels were installed underwater to bring the delivery voltage down to suitable levels before powering the common electrical or electronic components and SIs.

3.2 Medium voltage power converter

Generally speaking, the delivery voltage level depends on the insulation level of the subsea coaxial cable. The commercially available subsea cable is rated at about 10 kV, which is considered medium voltage. One PN equips one medium voltage power converter (MVC) for voltage reduction. Using such a converter in the deep sea is a great challenge as there are several requirements, most of which are more stringent than in a terrestrial system. These requirements include: (1) The converter should be small enough to fit inside a modestly sized pressure vessel. Vessels with smaller sizes can endure higher pressure, which is important for underwater equipment applications. Thus, the converter must have a simple electrical topology and compact structure. (2) The converter should be highly reliable. Repair or replacement may be more expensive than building a new one, and is sometimes even impossible. (3) The converter should have a high power density, as it needs to convert a significant amount of power, while its size is restricted by the pressure vessel. (4) The converter should be highly efficient, because the heat dissipation cannot be ignored when working at a high power level for a long time. (5) A special cooling method is necessary because the traditional fan cooling method is not available inside an airtight chamber.

Two methods have been proposed to meet the requirements of this converter. One is to build a large single converter that can sustain high input voltage and a large amount of power; the other is to stack a large converter with many small converter modules and ensure a connection. Electrical engineers have suggested stacking many small converter modules by connecting them in any combination (serial or parallel), at input or output, to meet any input-output specification. Compared with the concept of building in one converter, the stacking approach has several advantages, including: (1) Mature technology of the converter with low-voltage input and low-voltage output can be applied, which greatly shortens the research period; (2) Standardization of off-the-shelf components is available, and customization of electronic components is unnecessary; (3) A low-voltage metal-oxide semiconductor field-effect transistor (MOSFET) optimized for low $R_{DS(on)}$ (static drain-source on-resistance) is available, which can result in higher efficiency; (4) Small components are available, and a compact mechanical structure can be applied easily.

3.2.1 Synthesis of the medium voltage power converter

The required MVC is synthesized by stacking many basic building modules with serial input and parallel output (SIPO), as shown in Fig. 2. All modules are constructed with a topology of traditional forward and pulse width modulation (PWM) switching circuits that are operated at about 50 kHz. The modules have the same physical parameters and a specification of 400 V input and 375 V output with 400 W power supply. N modules stacked in a SIPO connection meet a specification of N×400 V input and 375 V output with N×400 W power supply. The input currents of the modules are equal to each other due to the serial connection. Given that the total input voltage is shared on all input stages with a special control strategy (which will be described in the next section), the input power of each module would be equal to each other. Supposing the transformers perform ideally, then the output current of each module would be equal to each other, as they have the same output voltage. Hence, the total conversion power would be equally shared for each module.

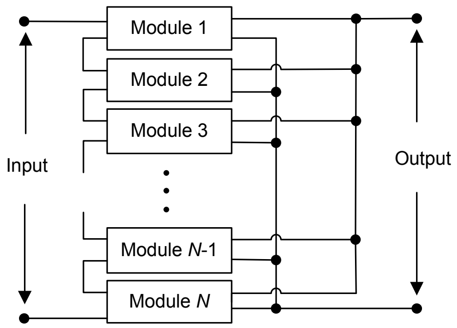


Fig. 2 Top-level block diagram of the synthesized converter

3.2.2 Control loop

Input voltage sharing for each module is the precondition for the analysis of power sharing. A special control strategy is necessary to achieve the precondition in which the input voltage is equally shared at all input stages. Generally speaking, synthesis of modules by serial or parallel connection with an individual controller to justify the duty ratio results in instability. Input voltage may practically shift to one stage due to mismatch of the ratio of transformers. Thus, when handling a relatively large input voltage by stacking many small modules with a SIPO connection, some modules may be destroyed by high voltage that is shifted from all other modules. Thus, more controllers are needed to guarantee the operational stability. Many control strategies have been proposed (Bhinge *et al.*, 2002; Ayyanar *et al.*, 2004; Giri *et al.*, 2004; Chen *et al.*, 2009; Huang *et al.*, 2009; Ruan *et al.*, 2009). When applying these methods, at least one controller per module is used to regulate individual PWM signals, and additional controllers, such as voltage sharing or current sharing controllers, are provided to modify the run-away situation. However, too many controllers will cause the structure to become complicated and lower its reliability.

A common duty ratio control strategy, initiated by Giri *et al.* (2006) and Vorperian (2007), greatly reduces the complexity of converter controllers. In this strategy only one controller is required. The controller works at peak current mode in which a common output voltage-sensing loop directly provides a current reference to an inner current loop where its current sample is sensed from the inductor current of any basic building module. Using this control mode, the input voltage will be shared by modules based on the inherent voltage balancing property of stacking connection. Some turbulence occurring in a module might impact directly only the total output, and not other modules, because there is no feedback between modules. The re-regulated control signal, based on the reshape output, makes actions synchronous to all modules, so that there would be no run-away problem. Individual components, such as the turn ratio of the isolated transformers, cannot be identical and certainly may induce different values between modules, but actually such differences do not violate the input voltage-sharing state, even in transient scenarios.

With this common duty ratio control strategy, only one controller is used for the converter (Fig. 3). Two feedback signals representing the output voltage and input current, respectively, are sampled and sent into the controller to form the peak current control mode. The feedback current signal aims to improve the converter dynamics and protect it at a current-limit mode. The PWM signal regulated in the controller according to the feedback signals is sent to drive the MOSFETs of each module after being enhanced by isolated MOSFET drivers. Special controllers are no longer needed to guarantee input voltage or output current sharing. Another advantage inherent to this control strategy is that even if one or more modules are shorted out at the input, the total input voltage can be re-shared within the remaining modules. Thus, input voltage sharing is not violated. This natural rebalance feature makes this type of synthesized converter more reliable.

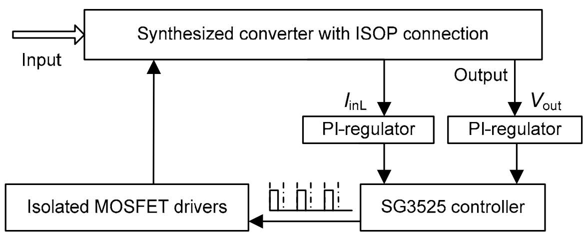


Fig. 3 Schematic of the control method based on the common duty ratio

3.3 Low-voltage power converters

The output of the MVC is 375 V. SIs, however, are mostly powered at 48 V or 24 V. Thus, more conversions are necessary for further distribution. An external load converter provides 48 V and 24 V for SIs, and an inner load converter provides multi-level voltages for nodes, including 24, 15, 12, and 5 V (Fig. 4). Both inputs are attached to the output of the MVC. An input filter applied improves the quality of the 375 V. Similar to the construction of the MVC, both load converters are built by stacking several basic building modules. Compared with building from the ground up, which offers a moderate solution, direct use of off-the-shelf modules is less costly and results in higher efficiency. The external load converter is structured by stacking modules by parallel input and parallel output (PIPO) to meet the specification of 375 V input and 48 V or 24 V output (Table 1). To ensure current sharing between modules, a common duty operation strategy is used through careful configuration. The optimum input of suitable converter modules is 375 V, which is the reason why the output of the MVC is fixed at this level. Two voltage levels are provided by an external load converter for alternative selection. The stack numbers are decided by

$$N_i \geq \frac{kP_{\max}}{P_i}, \quad i=1, 2, \tag{1}$$

where k is the power redundancy factor, $k\in[1, 2]$, $P_{\max}$ is the required maximum power, and P_i is the maximum power of one module.

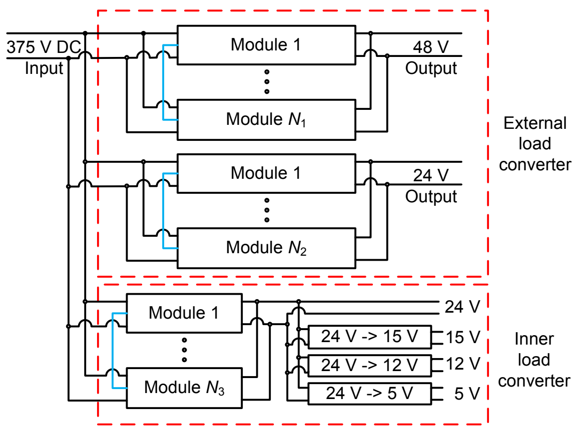


Fig. 4 Structure of the low-voltage power converters

The inner load converter provides various voltage levels. Two steps are used for this conversion; thus, the voltage-reduced ratios of modules can be even smaller to achieve better performance. First, it is carried down to 24 V with stacking modules. Then three more modules (Table 1) are attached at its output to provide various voltages. The inner load is small, so stacking each level is unnecessary.

Table 1 VICOR® module parameters

Module mode	Input voltage (V)	Output voltage (V)	Power (W)
V375A48H600BL	225–425	48	600
V375A24C600BL	225–425	24	600
VI-JW2-CW	18–36	15	100
VI-JW1-CW	18–36	12	100
VI-JW0-CY	18–36	5	50

3.4 Power distribution and management system

The power distribution and management system applied at all nodes rations the power and monitors the node state (Fig. 5). The external converter directly provides power for external SIs via science connectors. An external load control and monitor unit (ELCMU) monitors and manages each external load power state. Relatively autonomous actions of protection and isolation would be activated to protect the power system from damage or collapse, when faults caused by insulation damage, connector leakage, ground fault at instruments and others are detected. Manually forced actions can be implemented by commands sent from the shore station via the communication system. Meanwhile, an inner load control and monitor unit (ILCMU) that has broadly the same functions as the ELCMU is installed to monitor the inner load power state. Control system vessel sensors (CSVSs) and power vessel sensors (PVSs) are integrated in this sub-system to detect the inner physical states, such as temperature and moisture, of the control system and power vessels. Data from PVS, CSVS, ELCMU, and ILCMU are received by the node controller (a stack of PC/104 boards composed of one CPU board, a flash storage, and two analog/digital I/O boards). This node controller has an Ethernet LAN network interface for communication. Moreover, a 375 V power branch, along with a pair of optical fibers, is directly routed to the SN connector to cascade an SN. The current power distribution and

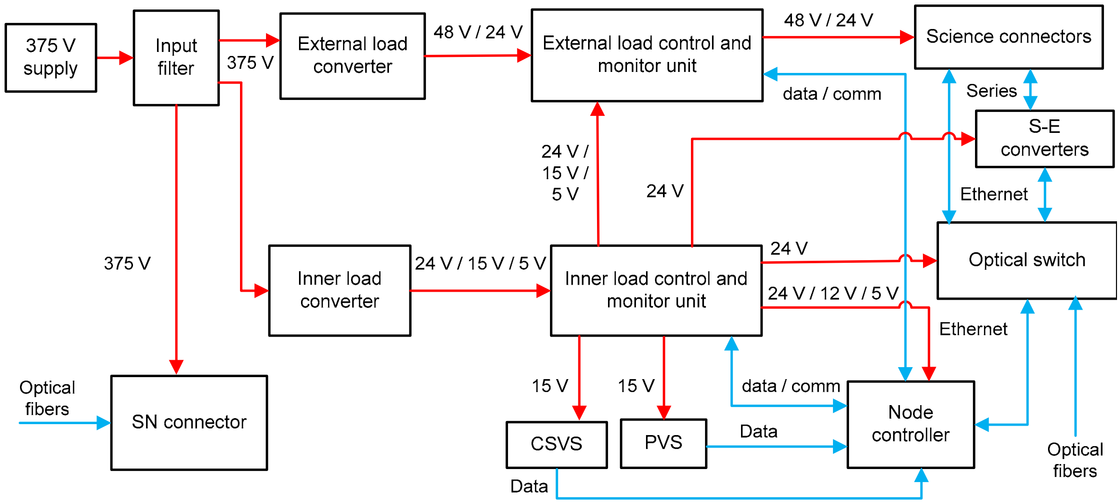


Fig. 5 Diagram of the power distribution and management system

management system and the communication system constitute the node control system, and are housed inside the control system's pressure vessel.

3.5 Heat dissipation

When power conversion reaches the maximum rating, the heat generated by electrical components can reach hundreds of watts. Traditional heat dissipation methods of air-forced convection, such as fan cooling, are not available here. Heat is difficult to pump out of the vessel even though the outside sea is an ideal heat conductor, because the heat conduction rate between air and the metal surface is very low. The inner temperature will rise dramatically when a large amount of redundant heat is trapped inside. Thus, a solution for reducing the heat resistance between heat sources and the vessel inner surface is required. Two methods are proposed here.

In the first method, the vessel will be filled with de-electrical cooling oil. Oil with a high heat conduction rating will form a low resistance conduction path between heat sources and the vessel surface. The oil with excellent insulation capacity also lowers the probability of discharge among circuit pins, which then increases the operational reliability. However, a disadvantage exists for filling the vessel with oil. Oil will expand when heated, even when the temperature of the vessel remains low due to cooling by the surrounding seawater. Thus, the rising oil pressure due to high temperatures should be carefully considered. The pressure needs to be limited to a certain level to avoid failure in the performance or structure of electrical components, such as electrolytic capacitors. The proposed method is to leave a certain volume of high compression ratio air in the air chamber for pressure release. Based on the Clapeyron theory, and supposing the rising pressure is lower than 0.5 MPa, we can ignore the nonlinear effect and derive

$$\frac{PV_{\text{air}}}{T}=\frac{P'V'_{\text{air}}}{T'}=\frac{P'V_{\text{air}}}{T+\Delta T}\left(1-\frac{V_{\text{oil}}\alpha\Delta T}{V_{\text{air}}}\right), \tag{2}$$

where P is the original air pressure (Pa), T is the original temperature (K), V_{air} is the original air volume (L), V_{oil} is the original oil volume (L), P' is the final air or oil pressure (Pa), V'_{air} is the final air volume (L), T' is the final temperature (K), α is the thermal expansion coefficient, and ΔT is the temperature difference (K).

Thus, the volume in the air chamber can be prescribed by

$$V_{\text{air}}=\frac{P'V_{\text{oil}}\alpha T\Delta T}{P'T-P(T+\Delta T)}. \tag{3}$$

For the given values of P, P', T, ΔT, we can calculate the required pressure-released air volume.

In the second method, a mechanical conduction path is constructed between heat sources and the vessel's inner surface. Filling oil is not suitable where special components are incompatible with oil. In addition, the shortage of oil features and the heat expansion can make the first method an unwise choice. The mechanical conduction method is better in some cases in which, for example, the heat sources are precisely centralized. Heat can be quickly conducted in the vessel and to the cold seawater by constructing a low-heat-resistance path between such kinds of heat sources and the vessel surface.

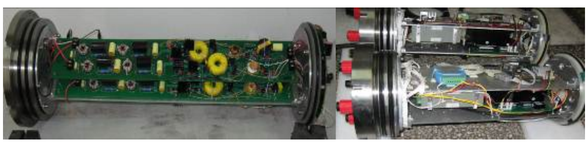
The MVC has many heat points that cannot be centralized, so it needs to be cooled using the first method. The low-voltage power converters are built using off-the-shelf modules that have a centralized heat dissipating plate; thus, they can be cooled with the second method. Detailed instances applied are presented in the next section.

4 Validation of the prototype

A prototype including a PN with two science ports, an SN with two additional science ports, and a shore station was built in the laboratory, powered at about 2000 V. A full validation study was carried out with the prototype.

4.1 Realization of the prototype

The PN was composed of a power vessel (PV) and a control system vessel (CV), while the SN was composed of only a CV. Housed inside the PV was an MVC with a specification of 2000 V input, 375 V output, and 2000 W maximum power. Housed inside the CV were the low-voltage power converters, the power distribution and management system, and the communication system. Both the PV and CVs were constructed in the laboratory, as well as their inner components (Fig. 6). Their external dimensions were Φ290 mm×1150 mm and Φ290 mm×680 mm, respectively. Titanium alloy was used to machine the PV and CVs in consideration of long-term underwater applications.



(a) (b)

Fig. 6 Prototypes of the medium voltage power converter (a) and two control systems (b)

The MVC was produced by stacking the five modules introduced above under a SIPO connection and filled with de-electric transformer oil for heat dissipation when housed in PV. Using the first heat dissipation method, setting P=0.1 MPa, P'=0.2 MPa, T=293 K, ΔT=50 K, and knowing that α=0.0008/°C, $V_{total}=V_{oil}+V_{air}$=41 L, we obtained the air volume V_{air}=3.61 L. A ballonet with 3.61 L air was placed inside to enable pressure release. A tank test of large power conversion and heat dissipation performance of PV was conducted. The oil temperature rose by 19 °C, and oil pressure rose by less than 0.04 MPa when the output power was fixed to 1200 W and the input power was about 1460 W (Fig. 7). Moreover, to validate the inherent redundancy of the converter, a short fault was manually induced by bypassing one module's input using a mechanical relay when working at a steady state with 1800 V input and 500 W output. The 1800 V input and the converting power were re-shared on the remaining four modules. The output voltage remained unchanged and no spikes occurred at either input or output.

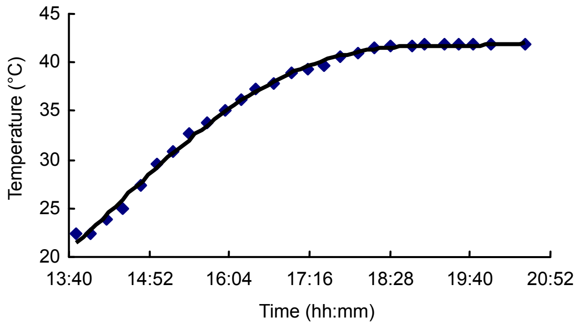


Fig. 7 Oil temperature behavior of the 2 kV@2 kW converter with 60% load

As the maximum power was limited to 2000 W, module numbers for stacking the low-voltage power converters can be set as $N_1=N_2$=2, N_3=1. Based on the second heat dissipation method, these converters were mounted on the aluminum framework of the control system and then directly mounted on one bulkhead of the CV, such that very low heat resistance could be attained. These converters, along with the power distribution and management system and the communication system, comprised the control system and focused on distributing and monitoring the load power supply. Before and after installation in the CV, full tests were carried out, especially on the heat dissipation performance of the power converters, and the fault detection and isolation ability of the power distribution and management system, to make sure that the inner temperature is in the allowable range and that the fault can be quickly isolated. The available power for science ports is shown in Table 2. The main inner components of the CV and their power consumptions are shown in Table 3.

Table 2 Power specifications of the laboratory prototype

Node	Part	Specifications
Primary	PV	Input: 1600–2400 V DC Output: 375±1 V DC Power: 2000 W
Primary	CV	Port 1: 48 V@500 W, Ethernet Port 2: 24 V@250 W, RS485
Secondary	CV	Port 1: 48 V@500 W, Ethernet Port 2: 24 V@250 W, RS232

PV: power vessel; CV: control system vessel

Table 3 Power consumption of inner components of CV

Instrument	Voltage (V)	Power (W)
Optical switch	24	8
Node controller	24, 12, 5	30
S-E converters	24	5
External load control and monitor unit	24, 12, 5	20
Inner load control and monitor unit	24, 12, 5	20
PVS	12	6
CSVS	12	6

CV: control system vessel. PVS: power vessel sensor; CSVS: control system vessel sensor

4.2 Tank test of the prototype system

The prototype system was assembled for system functional testing in the laboratory. A test of the input and output stability was conducted with four ports loaded with half of their ratings. Fig. 8 shows that the input voltage fluctuated between 1500 V and 2000 V, whereas the four outputs varied by less than 0.3 V. Some fault conditions such as output overload and short to ground were also manually conducted to test the reliability of this system before the prototype system was immerged into water. Additionally, the system was powered off to make sure no damages occurred when there was sudden power leakage at the shore station or delivery cable.

Functional validation of the whole system underwater was achieved by three validated deep-sea instruments (Table 4 and Fig. 9). The two temperature sensors were separately connected to the PN and SN. A camera system consisting of a deep-sea camera and two deep-sea lights was attached to the SN. All SIs, PVs, and CVs had been tested individually under 42 MPa in a pressure chamber before assembly into this system. The PN with validated sensors was immerged in a large tank; meanwhile, the SN with the two linked instruments was housed in a pressure chamber where the water pressure could reach 60 MPa (Fig. 10), so that we could simulate shallow- and deep-sea conditions synchronously. A PFE with an output of 2 kV DC@2.2 kW and a data management system (DMS) were fixed in a container nearby to form the shore station. The DMS was built using two industrial computers and local area network equipment. An underwater power cable and an underwater optical cable (both from SUBCONN®) were used to replace the subsea coaxial cable because the latter was too heavy and not suitable for operation in the lab. Power

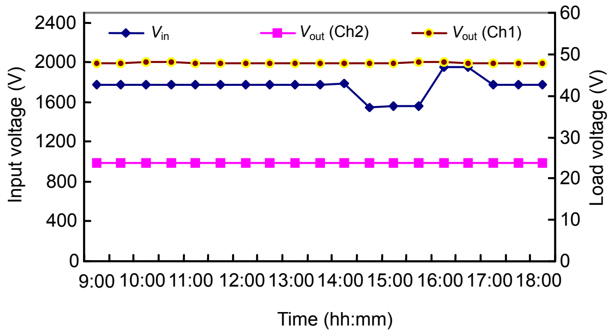


Fig. 8 Input and output voltages of power conversion

Fig. 9 Three test science instruments of the laboratory platform

Table 4 Definition of science instruments

Instrument	Voltage (V)	Power (W)	Protocol
SI1	24	25	RS485
SI2	24	15	RS232
SI3	48	280	Ethernet

SI1, SI2: underwater temperature sensor; SI3: deep-sea camera system with two deep-sea lights

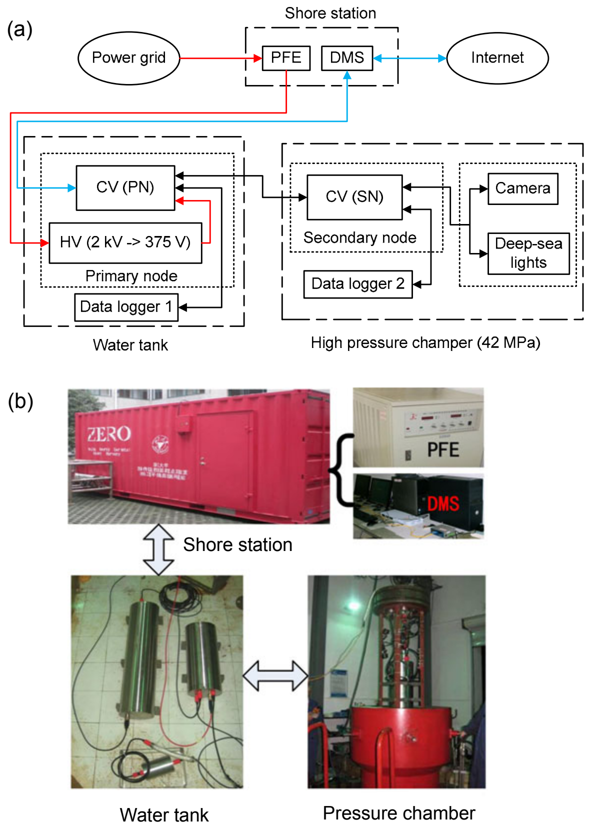


Fig. 10 Experiments on the prototype observatory system
(a) Sketch map of the laboratory platform; (b) The prototype and experimental setup

from the PFE was transmitted to the PN via the power cable and delivered directly to the PV. The 375 V output of the PV was routed to the CV. Inside the CV, the copper conductors were bifurcated: one powered the PN along with its linked instruments, and the other was routed to the SN along with a pair of optical fibers used for communication.

In this simulation, the output of PFE was fixed at about 2000 V, and all loads were turned on synchronously. The pressure in the high-pressure chamber was increased to 42 MPa (Fig. 11). The whole system operated steadily for a significant length of time without shutdown or reset. During the working period, some operations on two nodes or SIs were carried out: (1) The parameter values of the nodes were regulated by remotely logging into node controllers and online configuration; (2) Data from the two sensors or video from the camera was accessed through the TCP/IP protocol on the terrestrial terminal PC; (3) Commands, such as shutdown and reset of the camera system, were sent successfully to instruments; (4) Each load's supply and fault status and each vessel's inner temperature and physical status were monitored in real time at the shore station. All operations were done without mistake. Temperatures of inner vessels changed very slightly, as the power consumption was relatively small and, in turn, the dissipation heat was low. Validation of the fault detection and isolation functions underwater was not pursued because manually inducing fault conditions under water is impractical. This uninterrupted test lasted about 11 d, which was relatively short for a long-term (months to years) system. The operation results, however, showed that the issues identified were addressed using the methods presented and that abundant power could be supplied for underwater instruments. The following results were obtained from laboratory tests: (1) The DC power system was available for the underwater multi-node observatory system and flexible for extension; (2) Long-term serial power can be supplied to the underwater system after solving several key issues; (3) Gas can be used to release the pressure of the underwater oil chamber if an appropriate proportion of gas volume is used.

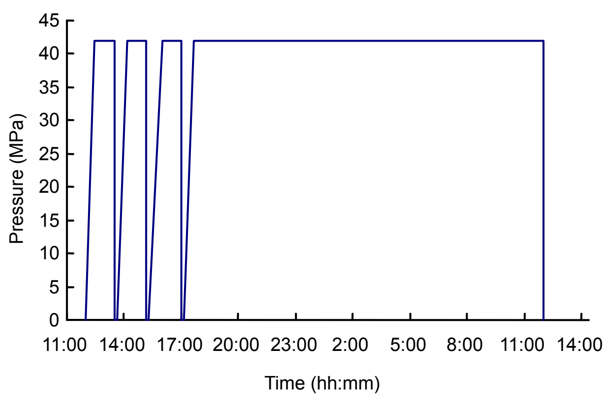


Fig. 11 Cycled pressure test on the secondary node

4.3 Deep-sea trial

During April 21 to October 26, 2011, an SN improved and developed based on the study of this laboratory system was successfully deployed in Monterey Bay in California, where the Monterey Accelerated Research Site (MARS) is located (36°43′ N, 122°11′ W). The MARS is a single node cabled observatory deployed at an approximate depth of 900 m and powered via a 52 km cable beginning from

Monterey Bay Aquarium Research Institute (MBARI) (Favali and Beranzoli, 2006). This SN was connected onto MARS by remotely operated vehicle (ROV) via a 50 m cable and became a secondary node of it. This improved SN can provide a maximum power of 4 kW through eight extendable ports. Each port was powered by a 1+1 redundancy supply. In addition, some technologies such as soft start, on-line ground fault detection, and heat dissipation were applied or improved to enhance the stability and reliability of the power system. During this test, the power available from MARS was limited to 500 W, so only two science packages, one from Tongji University and another from Ocean University of China, were connected onto this SN for functionality tests and each was limited to 200 W. During the half-year test, no fault or damage occurred in SN. Even after an accidental shutdown by MARS, the SN resumed perfectly after MARS power resumed. High quality power was supplied for attached instruments. Temperatures inside the SN were monitored online and the peak temperature was no more than 20 °C (the water temperature was about 10 °C). Synchronous remote operation was available through authorized addresses at the MARS's shore station or at the Chinese lab located on the other side of the Earth.

5 Conclusions

A cabled ocean observatory system was developed that can supply long-term power and wide bandwidth for subsea instruments in real time. We introduce a method of constructing a DC power system for a multi-node observatory system and describe in detail key techniques for delivery, conversion, distribution, and management of power, and heat dissipation. An experimental observatory system consisting of a PN and an SN was built in the laboratory, based on the method and techniques introduced. Experiments were carried out in a simulated ocean environment. We conducted a deep-sea trial of an improved SN by deploying it in Monterey Bay in California and connecting it onto MARS for long-term operation. Experimental results show that the proposed system is valid and could be a new approach for application in ocean observations. Facilities applied for ZERO are currently under development based on the study of the prototype system and will be deployed in early 2013 at the coastal area of Zhoushan (29°57′ N, 122°15′ E) in Zhejiang Province, China. However, some issues such as higher voltage (10 kV) and power (10 kW) requirements must be solved before a large-scale system can be actually applied. Compared with traditional approaches, the noteworthy advantages of the cabled ocean observatory system will offer a significant contribution to ocean research.

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