Frontiers of Information Technology & Electronic Engineering
www.jzus.edu.cn; engineering.cae.cn; www.springerlink.com
ISSN 2095-9184 (print); ISSN 2095-9230 (online)
E-mail: jzus@zju.edu.cn

Use of a coded voltage signal for cable switching and fault isolation in cabled seafloor observatories*

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Received Dec. 20, 2016; Revision accepted May 27, 2017; Crosschecked Nov. 8, 2018

Abstract: Cabled seafloor observatories play an important role in ocean exploration for its long-term, real-time, and in-situ observation characteristics. In establishing a permanent, reliable, and robust seafloor observatory, a highly reliable cable switching and fault isolation method is essential. After reviewing the advantages and disadvantages of existing switching methods, we propose a novel active switching method for network configuration. Without additional communication path requirements, the switching method provides a way to communicate with a shore station through an existing power transmission path. A coded voltage signal with a distinct sequence is employed as the communication medium to transmit commands. The analysis of the maximum bit frequency of the voltage signals guarantees the accuracy of command recognition. A prototype based on the switching method is built and tested in a laboratory environment, which validated the functionality and reliability of the method.

Key words: Cabled seafloor observatories; Cable switching and fault isolation; Coded voltage signal; Maximum bit frequency
https://doi.org/10.1631/FITEE.1601843 **CLC number:** TP271

1 Introduction

Oceans cover more than 70% of the planet and comprise over 95% of its living space. Ocean is a dynamic engine of the Earth driving energy transport and elemental cycles of the globe. To understand the complexity and interactive dynamics of ocean systems, long-term, real-time, and sustained data should be collected. Driven by these scientific requirements, cabled seafloor observatories were proposed which provide continuous power and broad bandwidth communication to operate a wide range of instruments (Favali and Beranzoli, 2006; Favali et al., 2015). Moreover, such observatories have been adopted in the oil and gas industry to monitor oil spills and gas hydrate releases.

Generally, power systems of cabled seafloor observatories can be divided into two major types: constant current (CC) mode and constant voltage (CV) mode (Howe et al., 2002). In a CC mode system, all nodes are serially connected. The CC mode has been proven to be robust against ground faults (parts of the system can continue to operate through a fault). Therefore, the CC mode can be applied to early warning systems in the seismically active zones for earthquake and tsunami detection. However, the CC mode is difficult to branch or mesh and has low energy utilization. Typical examples of observatories of the CC mode are the Hawaii-2 Observatory (H2O) (Petitt et al., 2002), the Marine Cable Hosted Observatory (MACHO) (Hsiao et al., 2014), and the Dense Ocean-floor Network system for Earthquakes and Tsunamis (DONET) (Kawaguchi et al., 2008). In a CV mode system, all nodes are connected in parallel

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* Project supported by the National Natural Science Foundation of China (Nos. 51409229, 41676089, and 51521064), the National High-Tech R&D Program (863) of China (No. 2012AA09A410), and the Zhejiang Provincial Natural Science Foundation of China (No. LQ14E070002)

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and a node can be installed anywhere if a branch is needed in the network. The CV mode can deliver more power and is favored for more general science-driven observatories. However, the CV mode system will completely collapse with a single conductor fault. Typical examples of observatories of the CV mode are the Monterey Accelerated Research System (MARS) (Howe et al., 2006), the Seafloor Observatory (OBSEA) (Aguzzi et al., 2011), the North East Pacific Time-integrated Undersea Networked Experiments (NEPTUNE) Canada (Kirkham et al., 2003), and the Regional Scale Nodes (RSN) (Yinger et al., 2013). NEPTUNE and RSN are in some sense hybrids of the two modes that require enough current to keep repeaters and branch units (BUs) going, with constant voltage for observation nodes and most of the power. Dummy loads are often required to guarantee the current in the backbone.

Cabled seafloor observatories are in the preparation phase in China, motivated by scientific requirements. Several CV mode tree topology experimental observatories with a single node or two nodes have been constructed in the East China Sea and the South China Sea, which are forerunners of upcoming large-scale, regional, and multi-node observatories (Xu et al., 2011; Zhang et al., 2015). With an increase in the number of nodes, a network becomes less robust because any fault in the nodes or cable may force the network into a power collapse. Considering that field repair work in the sea requires weeks or months depending on the weather and sea conditions, a highly reliable cable switching and fault isolation method is essential to ensure that the network can partly operate even in the presence of faults.

In this study, we focus on the design of a switching method for a CV mode network. A tree topology network is the simplest CV mode network. A ring or mesh topology can be a combination of several tree topology networks. We use the tree topology network as the application platform. The main features of the network are as follows (Fig. 1):

1. The network is composed of a shore station (SS), a submarine electrical/optical cable with a single conductor, BUs, and observation nodes, including primary junction boxes (PJBs), secondary junction boxes (SJBs), and terminal instruments (TIs).

2. Monopolar, negative, and high-voltage power (normally −10 kV) delivered through the cable with seawater as the return path is applied to reduce anode electrolytic corrosion, power loss, and construction loss (Chen et al., 2013).

3. A cluster of fibers carried in the hollow core of the cable can provide a high-bandwidth communication for the network.

4. Each observation node connects to a single-conductor spur cable branch from the backbone cable through BUs. The spur cable terminates with a cavity where copper and fibers are separated before routing to PJBs.

5. High-voltage power is reduced to a conventional level and then distributed to TIs, such as sensors and cameras, in the observation nodes.

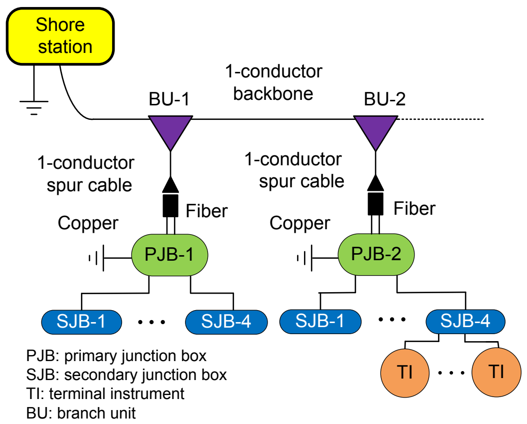

Fig. 1 Structure of a constant voltage (CV) tree topology cabled seafloor observatory

Theories and methods of fault isolation are quite mature for terrestrial electrical systems. However, these methods are not suitable for cabled seafloor observatories due to the specific nature of the submarine environment: (1) No compact off-the-shelf interrupters applied in terrestrial direct current (DC) electrical systems have shown a good performance in switching off DC currents at high voltage; (2) The monitoring system and power system are independent in a terrestrial electrical system (Tang and Ooi, 2007; Kempkes et al., 2011). However, the monitoring system of a submarine network is configured depending on the construction of the power system. This dependence means that an SS cannot control interrupters when a power system failure occurs.

Some studies have been conducted on cable switching and fault isolation for submarine DC networks. El-Sharkawi et al. (2005) and Lu and El-Sharkawi (2006) proposed two switching methods: one in which interrupters are controlled by the adjacent node (version 1) and the other in which interrupters are controlled through changing the voltage level and polarity (version 2). Optical supervisory control was proposed to control the interrupters (Thomas et al., 2013). This method is applied with a single conductor cable in the NEPTUNE Canada by Alcatel. Each design has advantages and disadvantages (Table 1). Chen et al. (2015) proposed an active controllable switching method based on discrete current as the command signals. However, subject to the maximum tolerable voltage and current of the cable and main components, the number of switching systems within a network is limited and cannot satisfy the needs of large-scale (tens or even hundreds of nodes) regional cabled seafloor observatories. We propose a novel active controllable switching method with a coded voltage signal as the communication medium. This switching method retains the merits of the former design and solves the problem of the limited number of nodes.

2 Design of the switching method

2.1 Concepts of the switching method

In this study, a coded voltage signal through the existing power transmission path is employed as the communication medium to transmit commands to the interrupter. No extra cable or device needs configuration, and therefore the cost is reduced. To distinguish from the normal function of the network, the switching systems work with the positive voltage supplied by the SS, whereas observation nodes work with the negative voltage.

Fig. 2 shows the application of the switching method in a CV mode network. The switching system is applied to the network in a parallel manner with seawater as the return path. For a tree topology network, one switching system with two interrupters is used to switch off the DC current for the backbone cable and the spur cable in BUs. For a ring or mesh topology network, two switching systems are required on each side of the backbone cable in BUs because the current may flow from either side. In addition, each switching system controls two interrupters.

Table 1 Comparison of the main characteristics of several switching methods

Switching method	Advantage	Disadvantage
El-Sharkawi et al. (2005) (version 1)	Communication occurs among SS, nodes, and BUs. Thus, all the interrupters are actively controllable and their status is observable.	A failed node can interrupt the controller's power supply and cause failure to large sections of the network. Arcing and restrikes of the interrupters need to be prevented as the system operates at −10 kVDC. Version 1 is sensitive to low impedance faults on backbone cables.
Lu and El-Sharkawi (2006) (version 2)	Any node failure can be isolated and the rest of the network maintains its function. Arcing and restrikes of interrupters are avoided.	Operations of the interrupters are autonomous and not actively controllable. Status of the interrupters is not observable.
NEPTUNE optical control	Communication exists between the SS and BUs. Thus, all the interrupters are actively controllable and their status is observable.	Arcing and restrikes of interrupters need to be prevented as the system operates at −10 kVDC. Switching system is highly complex and costly with the DC converter and optical devices.
Switching method proposed by Chen et al. (2015)	Interrupters are actively controllable. It is robust to low impedance faults of backbone cables. Arcing and restrikes of interrupters are avoided.	This method is suitable only for tree topologies without multiple branches. The number of switching systems is limited, subject to the maximum tolerable voltage and current of the system. Status of the interrupters is not observable.
Method proposed in this study	Interrupters are actively controllable. Arcing and restrikes of interrupters are avoided.	Status of the interrupters is not observable. This method is sensitive to low impedance faults on backbone cables.

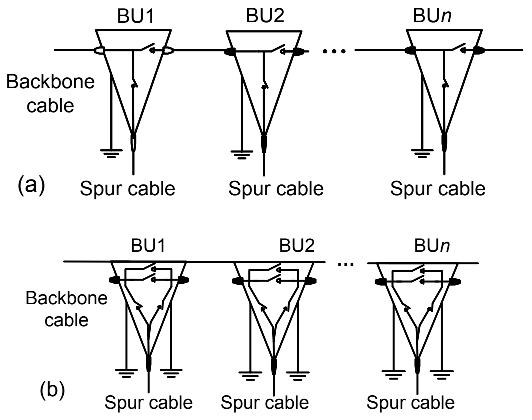

Fig. 2 Application of the proposed switching method in a CV mode network: (a) tree topology; (b) ring or mesh topology

A coded voltage signal consists of two signals imposed on DC voltage: high-level voltage representing code '1' and low-level voltage representing code '0'. Various combinations of codes '1' and '0' represent various commands based on the communication protocol. Regardless of the change in voltage levels, the switching system can always acquire a stable power supplier from the backbone cable to energize itself and latch the interrupters.

Fig. 3 shows the control logic of the switching method. The programmable power source in the SS controlled by the computer supplies the submarine cable with a series of different voltage levels as the command signals, based on the communication protocol. The command signal is sampled and transmitted to the switch controller, which is a logical circuit composed of a comparator, microcontroller unit (MCU), and drive circuits. Sampled signals are translated into standard digital signals for the MCU through the comparator. Finally, the MCU resolves the command signal and controls the drive circuit to trigger the operation of the interrupters.

2.2 Switching system based on the coded voltage signal

The main components of the switching system are as follows (Fig. 4):

1. Two latch-type vacuum interrupters S1 and S2 route the backbone cable and spur cable through high-voltage diodes D4 and D2, respectively. Each interrupter has two companion solenoids that are electrically isolated for closing and opening, separately.

2. The switching circuit consists of a switch controller, two closing solenoids (S1_C and S2_C), two opening solenoids (S1_O and S2_O), two voltage sampling resistors (R_{sam1} and R_{sam2}), a current limiting resistor (R_{CL}), a Zener diode (ZD), and a high-voltage diode (D1).

3. High-voltage diode D3 routes the backbone cable, which is parallel to S1 and D4. Note that D3 and D4 would not be required in a ring or mesh topology network.

4. The switching circuit connects to an electrode or directly to the metal case of BUs.

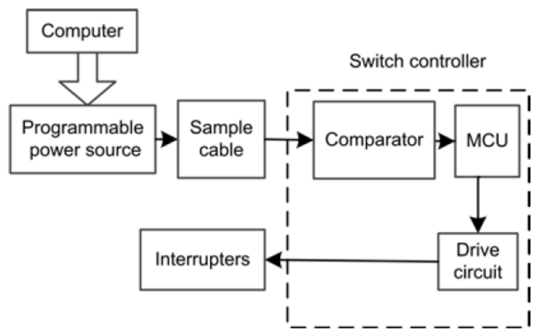

Fig. 3 Control logic of the proposed switching method

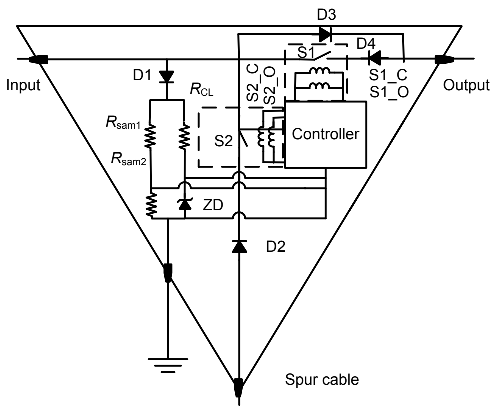

Fig. 4 Switching system based on the coded voltage signal

As mentioned before, the switching system works at a positive voltage to distinguish it from the normal voltage level required by the observation nodes (−10 kV to −6 kV). In the presence of the four high-voltage diodes, where D1 and D3 are in the opposite direction of D2 and D4, the current flows through D2 and D4 when the SS supplies a negative voltage for the observation nodes to work. Correspondingly, the current flows through D1 and D3 when the SS supplies a positive voltage to the network. In this mode, all the switching systems are powered. One advantage of the design of the circuit is that because the positive current is cut off by D2 and D4, almost no current flows through the interrupter during the operation of the switching system. Therefore, switching of the DC current in high voltage and the arcing phenomenon can be avoided to maximize the lifetime of the interrupter and improve the reliability of the network.

R_{CL} and ZD limit the current level that flows through the switching system and supply a stable voltage to energize the switch controller.

Three basic operation modes of the switching method are used: normal, configuring, and fault location modes.

1. Normal operation mode. A negative constant voltage (−10 kV) is supplied by the SS and all nodes connected to the network work in their normal state, whereas the switching systems are disabled due to the voltage polarity. When a fault occurs, the network requires a stop and diverts into the fault location mode.

2. Configuring mode. The network would change to the configuring mode in a scenario of fault isolation or network reconfiguration. In this mode, an SS reverses the polarity of the voltage and varies the voltage value within two certain levels based on a defined communication protocol. The interrupters are bypassed, and thus the status of S1 and S2 does not affect the voltage on the backbone cable. The switch controller is powered by the voltage in the backbone cable and receives the command signal by sampling the voltage across resistor R_{sam2}. The corresponding interrupter would be configured after the switch controller identifies the command signal. All observation nodes are disabled in this mode.

3. Fault location mode: The network would be forced into fault location mode when faults occur. Several kinds of conventional faults may occur: function faults of nodes, ground faults, and break faults. A function fault of a node is often not serious enough to pull down the voltage below the threshold, but presents a failure of communication in the normal operation mode. Ground and break faults would cause a network shutdown. A break fault indicates that the cable conductor is broken, but the insulation between the conductor and seawater is in the normal range. In the submarine environment, a break fault is often accompanied by a ground fault. Therefore, we discuss only the ground fault. The ground fault presents one or several weak points, such as shorted or low impedance to seawater. If a ground fault occurs in the spur cable or nodes, the switching systems are unaffected. The fault can be located using V/I measurement cooperating with the configuring mode. To locate the fault, all spur cables would be initially isolated from the backbone cable. Each spur cable connects back to the backbone cable and is energized with a negative low voltage (below the working voltage threshold of the nodes) according to the priority. A fault insulation resistance indicates a ground fault. However, if a ground fault occurs in the backbone cable, the switching system can do nothing, as the voltage level across the switching system cannot be accurately controlled to communicate with the switch controller in the configuring mode. When the fault is located, the network diverts to the configuring mode to isolate the fault.

2.3 Logic of command signal identification

Fig. 5 shows the definition of communication protocol composed of code ‘1’ or ‘0’. The communication protocol is divided into four parts: a start bit, data bits, a parity bit, and a stop bit. As the command signals on the power line are discrete, the switch controller is mostly in the sleep mode to reduce energy dissipation. The start bit is a special flag bit to separate valid information from slack bits. The start bit would activate the switch controller to receive the command signal from the SS. As the switch controller can be activated with only a falling edge, the slack bits are normally ‘1’ and the start bit is ‘0’.

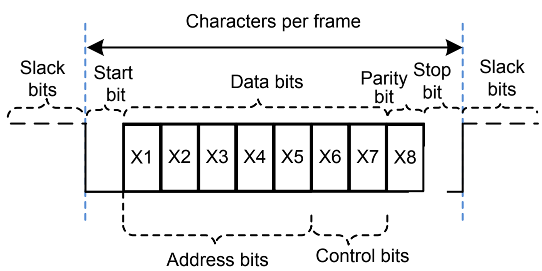

Fig. 5 Definition of the communication protocol

Data bits are the main parts of the communication protocol and are composed of two parts: address bits and control bits. Address bits include address information, which is the license to control a specific switching system. Each switching system has a unique address identification (ID). A specific switching system responds to the command only when its address ID is consistent with the address information included in the command signal. In this case, five bits constitute the address bits. In particular, the communication protocol can control 30 switching systems ($N=2^5-2$, where ‘00000’ and ‘11111’ are error-prone and excluded). The space of the address bits is determined by the number of controllable switching systems. Control bits indicate the final desired status of the interrupter. Each bit corresponds to one interrupter. Therefore, two bits constitute the control bits in this case. For each interrupter, ‘0’ indicates driving the opening solenoid and ‘1’ indicates driving the closing solenoid.

The parity bit is employed to ensure that the received command signal is correct. In addition, parity check is adopted for this communication protocol. When the value calculated based on the data bits is consistent with the parity bit in the command signal, the switch controller would operate.

The stop bit is a flag bit to tell the switch controller that the command signal is over. Then the switching controller would start to latch the interrupter to the right position. In this study, we select ‘0’ as the stop bit.

In the workflow of the switching system (Fig. 6), several judging procedures are performed to ensure that the right switching system accurately latches interrupter to the right position. Any incorrect or faulty decision result would lead the switch controller to return to the sleep mode and wait for the next command signal.

Accurately sampling the command signal and reducing bit error rate are significant in controlling switching system operation. However, some disturbances are unavoidable. For example, an electrical fluctuation or impulse caused by the environment or power source may generate a false start bit to the switch controller. In addition, the delay variation of electrical signals caused by parasitic parameters of the cable may result in an incorrect sampling result. An appropriate sampling method and bit frequency of the command signal would reduce the bit error and guarantee command recognition.

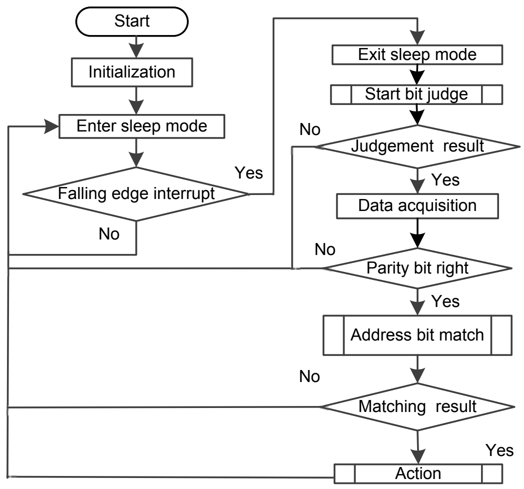

Fig. 6 Workflow of the proposed switching method

By comparing the advantages and disadvantages of several sampling methods in terms of off-the-shelf serial asynchronous communication, a 16 times sampling frequency was employed as the sampling method in this case. The sampling frequency is 16 times the bit frequency of the command signal (Fig. 7). When capturing the falling edge of the signal, the switch controller continuously samples a low-level signal at least eight times to ensure that the low-level signal is the true start bit, avoiding the disturbance of a false start bit caused by interference signals (Kevin, 1996). Thus, each bit would be judged using the 16 samples per data. If more than eight high-level signals exist in the 16 samples per data, the bit is judged as ‘1’; otherwise, the bit is judged as ‘0’.

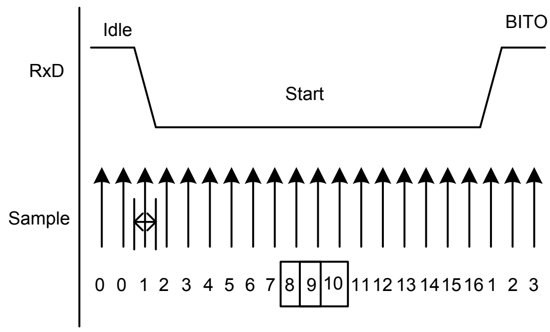

Fig. 7 The sampling frequency which is 16 times the bit frequency of the command signal

Define f_C as the bit frequency of the command signal (corresponding cycle T_C) and f_S the frequency of a sample clock (corresponding cycle T_S). We can obtain

$$f_S = 16 \times f_C, \tag{1}$$

$$T_C = 16 \times T_S. \tag{2}$$

Practical electrical/optical submarine cable used to construct the network has parasitic parameters of resistance (0.98 Ω/km), capacitance (0.179 μF/km), and inductance (0.37 mH/km), in the condition of 20 °C and standard atmospheric pressure. The existence of parasitic capacitance and inductance would hinder the variation of electrical signals in the cable, and thus present a delay time T_{delay} between two different voltage levels. To ensure the sample accuracy, sample cycle T_S must be larger than T_{delay}.

T_{delay} is determined by the parasitic parameters of the submarine cable. As the parasitic parameters of each kilometer of cable are nearly certain, T_{delay} is determined by the cable length. To determine the relationship between T_{delay} and the cable length, mathematical modeling of the cable was carried out using Matlab. Detailed analysis using RLC circuits (simple models composed of resistors, inductors, and capacitors) has been adopted by Grainger and Stevenson (1994). In this case, low frequencies required only evaluation; therefore, a simplified one-section RLC circuit was employed to model cables of a variable length (Fig. 8). A 1000-km cable was used as an example and the model included a serial 1000-Ω resistor, a serial 370-mH inductor, and a parallel 160-μF capacitor.

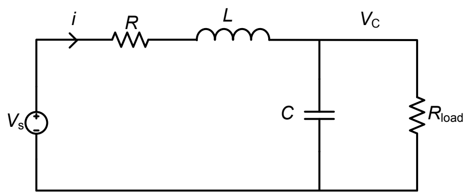

Fig. 8 RLC model simulating a 1000-km cable

For model construction, the switching system can be simplified as a constant resistor, whose value is nearly equal to R_{CL}:

$$\begin{cases} L\dfrac{di}{dt} = V_S - iR - V_C, \\ C\dfrac{dV_C}{dt} = i - \dfrac{V_C}{R_{load}}, \end{cases} \tag{3}$$

where R, C, and L are the parasitic parameters of resistance, capacitance, and inductance, respectively. R_{load} is the equivalent resistance of the switching system, whose value is constant at 12.5 kΩ, i is the current flowing through the submarine system, V_C is the voltage across the switching system which equals 200 V, and V_S is the voltage supplied by the SS which equals 300 V. The reference voltage in the comparator is 250 V. Variation curves between two voltage levels of the simulation results are shown in Fig. 9.

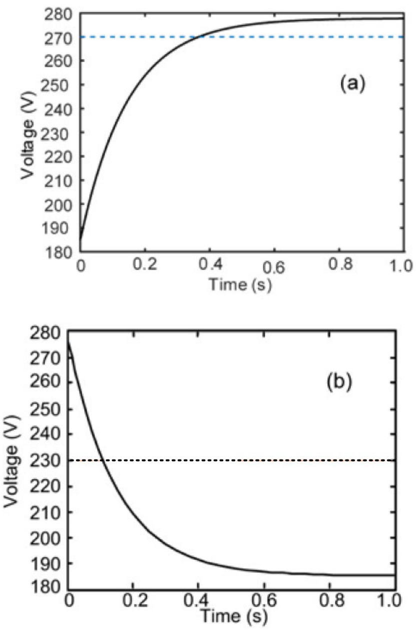

Fig. 9 Variation curves between two voltage levels: (a) 200 V to 300 V; (b) 300 V to 200 V

We consider the process of variation between two voltage levels to be completed when the variation exceeds 70% of the difference between two voltage levels, and provide some redundancy for the sampling accuracy. In other words, the variation between two voltage levels is the process when the voltage rises from 200 V to 270 V or declines from 300 V to 230 V. We define 230 V and 270 V as the threshold voltages.

When the cable reaches a certain length, the parasitic resistance of the cable cannot be ignored because it will cause a voltage drop. V_C is lower than V_S when the system is stable:

$$V_C = V_S \frac{R_{load}}{R_{load} + R}. \quad (4)$$

In this case, the stable voltages across the switching system are 186 V and 278 V. Delay time lengthens as the threshold voltage approaches the stable voltage. This phenomenon causes a difference between the rise delay time and fall delay time. As observed from the simulation results (Fig. 9), the rise delay time is about 0.366 s and the fall delay time is about 0.107 s. We define the larger time, namely, the rise delay time, as T_{delay}.

Fig. 10 shows the simulation results of the relationship between T_{delay} and cable length. T_{delay} increases with the cable length at an approximate exponential rate. When the cable reaches a certain length, T_{delay} becomes very large.

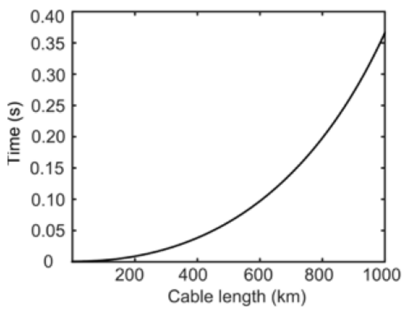

Fig. 10 Relationship between T_{delay} and cable length

T_{delay} is known for guaranteeing command recognition; thus, the duration of each command signal's bit T_C must be larger than 16 times T_{delay}. In addition, the maximum bit frequency f_C of the coded voltage signal is determinate.

3 Tests

A prototype based on the switching method was built in a laboratory to validate its functionality and reliability. In simulating practical application conditions, a test platform composed of 15 RLC circuits was constructed to simulate a 150-km submarine cable. Considering the parasitic parameters of the cable, each RLC mode consisted of a serial 10-Ω resistor, a serial 3.7-mH inductor, and a parallel 1.6-μF capacitor to simulate a 10-km submarine cable. During the test, the switching system was constructed at the end of the model cable (Fig. 11).

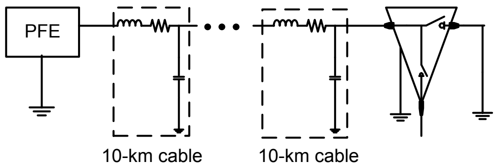

Fig. 11 Test platform with a 150-km model cable

A constant voltage DC source was employed as the power feeding equipment (PFE) to supply command signals to the platform (Fig. 12a). As analyzed previously, T_{delay} between two voltage levels is about 0.0046 s when the command signal is transmitted through the 150-km submarine cable. Therefore, the duration of each command signal's bit must be larger than 0.075 s to avoid identification errors. Limited by the maximum frequency of the PFE's output variation, we selected 1 Hz as the bit frequency of the command signal to test the switching system.

After testing the 150-km model cable in the laboratory, we had an opportunity to test the switching system in a practical 150-km submarine cable (Zhongtian Technology Submarine Cable Company Limited) to validate the switching function (Fig. 12b).

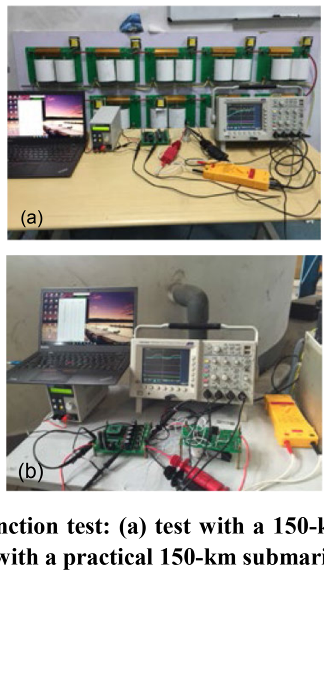

Fig. 12 Function test: (a) test with a 150-km model cable; (b) test with a practical 150-km submarine cable

3.1 Test with the 150-km model cable

In this case, 200 V and 300 V were selected as the two voltage levels and the reference voltage in the comparator was 250 V. Therefore, the practical voltages across the switching system were about 197.6 V and 296.4 V.

The condition in which the latch-type vacuum interrupter operates is that the voltage across the solenoid must be maintained above 16 V for at least 15 ms. An energy-storage capacitor connected in parallel with each solenoid was configured in each drive circuit to provide the energy to drive the solenoid. Before a response to the command signal was made, sufficient time was provided for the energy-storage capacitor to store sufficient energy. As the energy storage time was about 15 s and each command signal would last 10 s, the duration of slack bit before each command signal had to be longer than 5 s.

Address ID of the switch system was '10101'. Four command signals were sent in sequence to the switching system. The test results are shown in Fig. 13.

Channel 1 (blue line) represents the input command signals across the switching system. Channel 2 (cyan line) represents the voltage across the energy-storage capacitor for the closing solenoid. Channel 3 (red line) and channel 4 (green line) represent the voltage across the interrupter's closing and opening solenoids, respectively.

Before the switching system could respond to a command, the voltage across the energy-storage capacitor was already about 22.7 V; thus, the energy was sufficient to drive the interrupters' solenoids (Fig. 13). Fig. 13a shows the command signal to close the interrupter. When the switch controller received the stop bit, the driving signal was sent to the corresponding drive circuit. The energy stored in the capacitor was released to the closing solenoid to close the interrupter of less than 3 ms, with a voltage pulse across the closing solenoid at the same time. In general, the driving signal from the switch controller would last 100 ms, which was sufficient for the drive circuit to drive the solenoid. Subsequently, the capacitor restarted to store energy for the next command signal. During the operation, no action was performed by the opening solenoid. Fig. 13b shows the command signal to open the interrupter. Similar

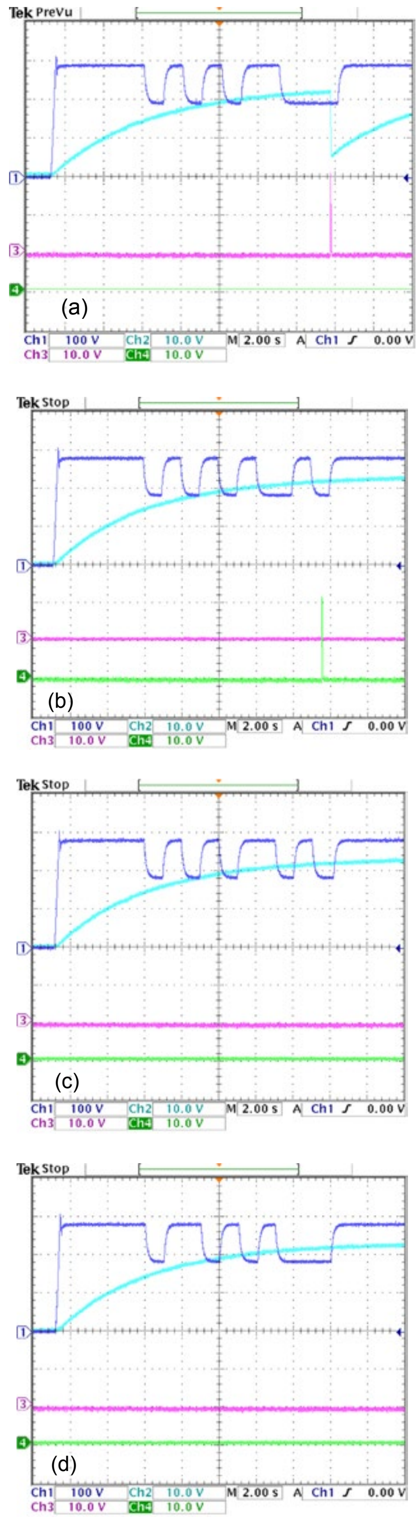

Fig. 13 Test results with a 150-km model cable: (a) command to a close interrupter; (b) command to an open interrupter; (c) command with a wrong parity bit; (d) command with non-corresponding address information

References to color refer to the online version of this figure to Fig. 13a, a voltage pulse across the opening solenoid indicated that the energy stored in the capacitor was released to the opening solenoid to open the interrupter. Correspondingly, no action was performed by the closing solenoid and its energy-storage capacitor. Figs. 13c and 13d show two cases of wrong command signals; Fig. 13c shows a command signal with a wrong parity bit, and Fig. 13d shows a command signal with non-corresponding address information '11010'. Neither of the two command signals would trigger the operation of the interrupter.

Reliability is the first priority for a submarine system. Thus, a durability test was conducted by cyclically transmitting different command signals and continuously once every 20 s for a total of 24 h to validate the reliability. The opening and closing solenoids were driven 2160 times. During the test, no miss operations were monitored. Given that, faults and maintenance are rarely observed during the lifetime of a seafloor observatory, and the switching circuits operate only a few times. The durability test can sufficiently validate the reliability of the switching system. The temperature of the switching system was monitored once every 10 min in the first hour and then once every hour with thermal imaging to test whether unreasonable heating points were present that may affect the component's lifetime. Consistent with the analysis of the switching circuit, the main heating point was R_{CL}. The temperature of R_{CL} gradually rose and was maintained at about 58.0 °C after 30 min, which is reasonable for the component.

3.2 Test with a practical 150-km submarine cable

The test process was similar to that of the 150-km model cable test in the laboratory. Unlike in the laboratory test, four high-voltage diodes (D1, D2, D3, and D4) were constructed in a printed circuit board that routed the switching system to simulate the practical application environment (Fig. 4). The four high-voltage diodes adopted different components according to their different application requirements. The repetitive peak reverse voltage of D1 and D3 was 16 kV, as the normal operation voltage was 10 kV. Their peak on-state voltage was very small to avoid the increase in difference between PFE's and switching system's voltages. The other two high-voltage diodes (D2 and D4) selected the diode with 800 V repetitive peak reverse voltage and a high mean on-state current, as the current can be as high as 10 A in the normal operation of the network.

Four command signals were sent to the switching system in sequence. The test results are shown in Fig. 14. The four signal channels represent the same information as for the test results with the 150-km model cable.

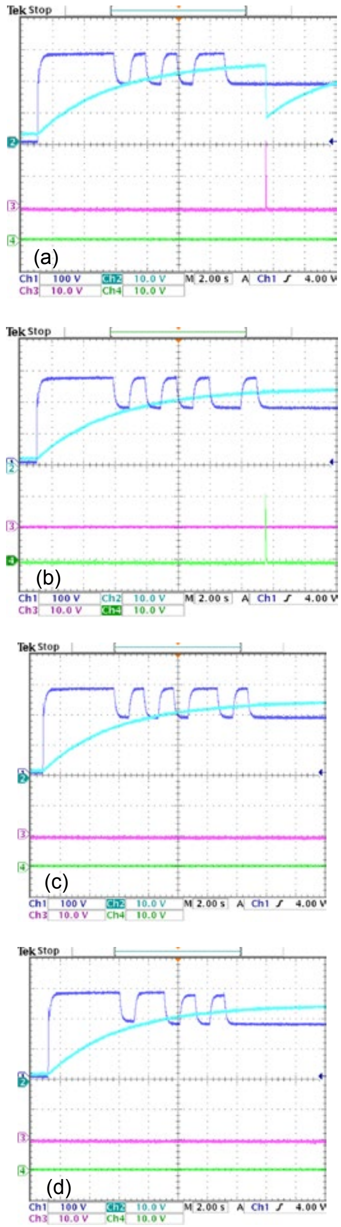

Fig. 14 Test results with a practical 150-km submarine cable: (a) command to a close interrupter; (b) command to an open interrupter; (c) command with a wrong parity bit; (d) command with non-corresponding address information

References to color refer to the online version of this figure

The function of the switching system was validated with the 150-km practical submarine cable. No apparent difference was observed in comparison with the test results from the 150-km model cable. Limited by the test time permitted by the company, only 10 circulations of the four command signals were transmitted to the switching system. No miss operations were monitored during the entire test.

4 Discussion and conclusions

An actively switching method for cable switching and fault isolation of cabled seafloor observatories based on a coded voltage signal was proposed in this study. Operating at zero current and nearly zero voltage maximizes the lifetime of the interrupters depending on the design. The series of tests on the established prototype validated the functionality and reliability of the system. Before the switching system is constructed in a large-scale observatory involving hundreds or even thousands of kilometers of cable, the following considerations must be addressed:

1. The switching system was directly configured based on the network power transmission path without additional cable or devices, and the communication link between an SS and switching systems was one-way. Therefore, the state of the interrupters was unobservable by the operation staff. In the laboratory tests, a multimeter was used to validate whether the corresponding interrupter accurately operated. In practical applications, the insulation resistance of the network, the voltage and current of the SS in the normal operation mode, and the communication between the SS and the objective node can indicate whether a specific section is isolated under the premise of the network topology.

2. In laboratory tests, T_{dealy} presented in Figs. 13 and 14 actually reflected the adjustment time of the output of the PFE, which should also be considered in practical operations. When the cable is quite long, T_{dealy} of the farthest switching system can reach up to seconds, and therefore each command signal must continue for several minutes or even longer to guarantee the reliability of command recognition.

3. Some natural phenomena, such as tides, steady ocean water flows, telluric currents, and geomagnetic fluctuations associated with solar diurnal variation, may introduce fluctuating current in a large-scale seafloor network (Meloni et al., 1983). The general induced voltage is usually less than 1 mV/km, which is much smaller than the difference between two voltage levels. This noise does not affect this switching method on a powered cabled system. However, intense solar storms may induce extra high potential on the long cable and destroy the insulation, as sometimes the phenomenon occurs with terrestrial power grids. Parallel to the switching systems, certain surge suppression circuits could be configured to release the energy induced by solar storms and protect the switching systems in practical applications.

4. The number of controllable switching systems is also limited by the voltage rating of the cable. As the number of switching systems increases, the current flowing through the cable also increases, resulting in a voltage decline between the SS and the farthest switching system. To accurately recognize the command signal, the interval between the two voltage levels must be large. As the voltage rating of a cable is normally 10 kV, there can be tens or even hundreds of switching systems, which is sufficient.

5. In practical operations, fault or maintenance work is rare and happens only a few times over the project lifetime. Some operations are common and their control targets are all switching systems, including closing all backbone cable interrupters and closing and opening all spur cable interrupters. To reduce the configuration time, a special address ID would be selected. All switching systems would respond to command signals with the special address ID.

6. The scheme proposed in this study may not be the optimal signal processing scheme but a suitable scheme considering the hardware configuration requirements and the amount of controller's consumption.

With these considerations, additional tests, such as function tests with a practical submarine cable and observation nodes, must be performed as the next step to fully validate the compatibility of the switching system with a unique submarine environment.

References

Aguzzi J, Mànuel A, Condal F, et al., 2011. The new Seafloor Observatory (OBSEA) for remote and long-term coastal ecosystem monitoring. *Sensors*, 11(6):5850-5872.

https://doi.org/10.3390/s110605850
Chen Y, Yang C, Li D, et al., 2013. Study on 10 kVDC powered junction box for a cabled ocean observatory system. *China Ocean Eng*, 27(2):265-275. https://doi.org/10.1007/s13344-013-0023-y
Chen Y, Howe BM, Yang C, 2015. Actively controllable switching for tree topology seafloor observation networks. *IEEE J Ocean Eng*, 40(4):993-1002. https://doi.org/10.1109/JOE.2014.2362830
El-Sharkawi MA, Upadhye A, Lu S, et al., 2005. North East Pacific Time-integrated Undersea Networked Experiments (NEPTUNE): cable switching and protection. *IEEE J Ocean Eng*, 30(1):232-240. https://doi.org/10.1109/JOE.2004.839938
Favali P, Beranzoli L, 2006. Seafloor observatory science: a review. *Ann Geophys*, 49(2-3):515-567. https://doi.org/10.4401/ag-3125
Favali P, Beranzoli L, de Santis A, 2015. Seafloor Observatories. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-11374-1
Grainger J, Stevenson W, 1994. Power System Analysis. McGrawHill, New York, USA.
Howe BM, Kirkham H, Vorperian V, 2002. Power system considerations for undersea observatories. *IEEE J Oceanic Eng*, 27(2):267-274. https://doi.org/10.1109/JOE.2002.1002481
Howe BM, Chan T, Sharkawi ME, et al., 2006. Power system for the MARS ocean cabled observatory. Scientific Submarine Cabled Conf, p.121-126.
Hsiao N, Lin T, Hsu S, et al., 2014. Improvement of earthquake locations with the Marine Cable Hosted Observatory (MACHO) offshore NE Taiwan. *Mar Geophys Res*, 35(3):327-336. https://doi.org/10.1007/s11001-013-9207-3
Kawaguchi K, Kaneda Y, Araki E, 2008. The DONET: a real-time seafloor research infrastructure for the precise earthquake and tsunami monitoring. OCEANS, p.121-124. https://doi.org/10.1109/OCEANSKOBE.2008.4530918
Kempkes M, Roth I, Gaudreau M, 2011. Solid-state circuit breakers for medium voltage DC power. IEEE Electric Ship Technologies Symp, p.254-257. https://doi.org/10.1109/ESTS.2011.5770877
Kevin S, 1996. VHDL for Programmable Logic. Prentice Hall, New Jersey, USA.
Kirkham H, Lancaster P, Liu CC, et al., 2003. The NEPTUNE power system: design from fundamentals. Proc Int Conf on Physics and Control, p.301-306. https://doi.org/10.1109/SSC.2003.1224167
Lu S, El-Sharkawi MA, 2006. NEPTUNE power system: detection and location of switch malfunctions and high impedance faults. IEEE Int Symp on Industrial Electronics, p.1960-1965. https://doi.org/10.1109/ISIE.2006.295873
Meloni A, Lanzerotti LJ, Gregori GP, 1983. Induction of currents in long submarine cables by natural phenomena. *Rev Geophys Space Phys*, 21(4):795-803. https://doi.org/10.1029/RG021i004p00795
Petitt RA, Harris DW, Wooding B, et al., 2002. The Hawaii-2 Observatory. *IEEE J Ocean Eng*, 27(2):245-253. https://doi.org/10.1109/JOE.2002.1002479
Tang L, Ooi B, 2007. Locating and isolating DC faults in multi-terminal DC systems. *IEEE J Power Del*, 22(3):1877-1884. https://doi.org/10.1109/TPWRD.2007.899276
Thomas R, Akhtar A, Bakhshi B, et al., 2013. Data transmission and electrical powering flexibility for cabled ocean observatories. OCEANS, p.1-7. https://doi.org/10.23919/OCEANS.2013.6741349
Xu H, Zhang Y, Xu C, et al., 2011. Coastal seafloor observatory at Xiaoqushan in the East China Sea. *Chin Sci Bull*, 56(26):2839-2845. https://doi.org/10.1007/s11434-011-4620-y
Yinger P, Tennant P, Reardon J, et al., 2013. Commissioning of a system that terminates on the seafloor. OCEANS, p.1-6. https://doi.org/10.1016/j.oceaneng.2012.11.007
Zhang F, Chen Y, Li D, et al., 2015. A double-node star network coastal ocean observatory. *Mar Technol Soc J*, 49(1):59-70. https://doi.org/10.4031/MTSJ.49.1.7