Switching High Voltage DC Power in Branching Units of Large-scale Cabled Seafloor Observatories

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Abstract. Cabled Seafloor Observatories (CSOs) are powered by shore stations with DC voltage levels up to -10kV. When a backbone or spur cable fault occurs, the power system must isolate the fault by disconnecting the faulty segment quickly. So the BUs installed in the backbone cable need to carry out the switching operation under high voltages (HV). However, DC circuits have no zero-current points and the fault currents will rise rapidly, bringing a big challenge to the switching on/off operation. In this paper, we have purposed an HVDC circuit breaker based on series-connected IGBTs with voltage balance. Under the backbone voltage of -10kV and a peak current of around 14A, the simulation results show that the proposed design is feasible, with the switching-off time about 1ms.

1. Introduction
Cabled Seafloor Observatories (CSOs) can on-line observe the deep ocean with real-time and in-situ experiments. Large-scale CSOs consist of shore stations, primary and secondary junction boxes, instrument platforms and electro-optic cables, as well as branching units (BUs) and repeaters as backbone devices [1]. Shore stations provide abundant power to ensure the normal operation of the system. A BU connects the backbone cable with a spur cable which is linked to a primary junction box. In case of a backbone or spur cable fault occurs, the power switches in the nearest BUs must be opened to isolate the fault so that the system will remain normal operation.

In traditional CSOs, the entire system will shut down due to voltage collapse when a cable fault occurs. Then the system enters a fault location mode, and restarts with the backbone voltage at a low positive voltage of +500V. The shore stations make voltage and current measurements and the system diagnoses and locates the fault cable sections, then enters the fault isolation mode [1]. During the fault locating and isolating process, the undersea observatory will stop working. The system will be restored operation after isolating the fault.

The biggest challenge is to achieve on-line HVDC power switching in each branch node of CSOs, for the system can remain operation during a fault. So the HVDC switching unit in BU is critical for the protection and maintenance of CSOs. In this paper, a switching circuit based on series-connected IGBTs is proposed for fast fault isolation.

2. High Voltage Power Switching in BUs

2.1. Technical Features
During the normal situation, the backbone current of CSOs is about 0.5-10A under -10kV. Designing a switching circuit with the following technical features is quite important for reliability consideration.

- Detecting and isolating faults within a few milliseconds and restoring the energy in the system in a very short time after clearing the fault [2].
- Consuming low power during normal operation [3].
- Capable to tolerate short circuit current of dozens amperes.
- Compact and highly reliable.

There are 3 methods to achieve HVDC power switching. The first one is based on HV mechanical switches which have arc when cutting off the current [4]. Due to absence of a natural zero current crossing, it is hard to find a reliable way to extinguish arcs. Each switching operation causes damage to the mechanical switch. Therefore, it is not suitable for subsea equipment which is difficult to maintain. The second one is based on solid-state power electronic switches, which have the advantages of fast breaking speed and no arc operation. But the high power loss limits their use in large current systems [5]. The third one is to combine mechanical and solid-state solutions with their advantages [6]. As the power systems of CSOs have small current and high voltage, the power switching solution based on solid-state power switches may be the best choice. The biggest difficulty is that the maximum blocking Collector-emitter voltage of a single IGBT cannot reach this the voltage level of 10kV.

2.2. High Voltage Power Switching Solution

Figure 1 shows a typical power system feeding loads in parallel through an optic-electric submarine cable. The equivalent inductance of 300km cables is around 120mH, which may generate a high surge voltage across the switch during the current interruption.

![Figure 1. A typical power system of CSOs](image)

The proposed HVDC switching circuit for BUs is shown in Figure 2. It consists of IGBTs, RCD snubber circuits, clamp varistors, a mechanical isolation switch and a control unit. Multiple IGBTs are connected in series to achieve a high blocking voltage. The RCD circuits [7] achieve voltage balance of the series-connected IGBTs. The varistor is a surge arrester used to absorb system energy and clamp the voltage across the switch unit. The mechanical switch enables physical isolation. The control unit sends control signals to each IGBT according to the measurements of current sensors. Each BU consists of four such power switches as shown in Figure 1 [8].

![Figure 2. Topology of high voltage DC switching unit](image)
The primary current and voltage waveforms of a breaking operation shown in Figure 3. As soon as a fault occurs, the trunk current begins to rise linearly at the moment of $t_0$ because of the inductor. After a certain response time, the switch unit detects the fault current and the IGBTs are turned off at $t=t_1$. The current flowing through the IGBTs is transferred to the capacitors in parallel, and the voltages across the capacitors increase during charging. When the voltage across the series-connected IGBTs rises to the preset value of the varistor at $t=t_2$, the varistor’s resistance becomes very small, and the falling current transfers to the varistor during $t_2-t_3$. Then the fault current drops down from $t_3-t_4$ while the energy in the system is dissipated by the varistor. The current through the switch falls to zero at $t=t_4$ and capacitors discharge until their total voltages are equal to the power supply voltage. At last, the mechanical switch $S$ is turned off without arc to implement physical isolation.

![Figure 3. Current and voltage waveforms of a breaking operation](image)

2.3. Principle of Voltage Balancing Circuit

The voltage should be balanced among series-connected IGBTs in both dynamic and static conditions. The static unbalanced voltage is mainly caused by the inconsistency of IGBT leakage currents. Most factors that cause dynamic unbalanced voltage can be attributed to the inconsistencies in the driver parameters of the IGBTs and the dispersivities of the IGBTs.

2.3.1 Analysis of static voltage sharing circuit. When these series-connected IGBTs are off completely, the voltage of each IGBT is different from one another because of the leakage resistances. Each IGBT is parallel to a resistance $R_s$ that is far smaller than the leakage resistance, so that the voltage on each IGBT depends mainly on the voltage sharing resistance $R_{s,ces}$ [9]. We should ensure that the unbalanced ratio of the voltage across IGBTs is less than 10% under static condition. To ensure the blocking voltage of the switch unit, assume the maximum total voltage of the $n$ IGBTs is $2U_{dc}$ times of the power supply voltage. So the maximum blocking voltage of a single IGBT is $U_{ces} = 2U_{dc}/n$. Considering the extreme condition, maximum of the parallel voltage sharing resistor is

$$R_s \leq \frac{0.2U_{dc}}{n(i_{ces,max} - i_{ces,min})}$$

(1)

Where $i_{ces,max}$ and $i_{ces,min}$ are the maximum and minimum leakage current of the $n$ series-connected IGBTs. Paralleling voltage sharing resistor will make more power loss.

$$P_{Rs} \geq \frac{U_{dc}^2}{nR_s} = 5U_{dc}(i_{ces,max} - i_{ces,min})$$

(2)
2.3.2. Analysis of dynamic voltage sharing circuit. The circuit diagram of the IGBTs dynamic voltage sharing based on the RCD circuit (resistance $R$, capacitance $C$ and diode $D$) is shown in the snubber part of Figure 2. The current flowing through the IGBT which turns off firstly will transfer to the parallel buffer capacitor, which will charge the capacitor to increase the voltage of capacitor. Because the voltage of the capacitor cannot be changed immediately, it makes the voltage of the IGBT increase relatively slowly so as to balance the voltage of IGBTs [9].

Considering the most severe condition, the first IGBT turns off $\Delta t_{\text{off}}$ earlier than the rest of the IGBTs, where $\Delta t_{\text{off}} = t_1 - t_2$. The first one will withstand a higher voltage. In this situation, the maximal voltage difference between the first and final turn-off IGBTs is about equal to [8]

$$\Delta U_c \approx \frac{\Delta t_{\text{off}}}{C}$$

(3)

Assuming that the maximum allowable voltage difference is 10% of the maximum voltage of a single IGBT, the minimum snubber capacitance should be

$$C \geq \frac{\Delta t_{\text{off}} \cdot i_{\text{fault}}}{10\% \cdot U_{\text{CES}}} = \frac{5n\Delta t_{\text{off}} \cdot i_{\text{fault}}}{U_{\text{dc}}}$$

(4)

The RCD circuit charges and discharges the capacitor during every operation periodically, leading to higher power loss and slower switching speed.

The power loss of a breaking operation is equal to the energy stored in the fully charged capacitors.

$$E_c = \frac{1}{2} n C U_c^2 = \frac{1}{2} n \cdot \frac{5n\Delta t_{\text{off}} \cdot i_{\text{fault}}}{U_{\text{dc}}} \cdot \left(\frac{U_{\text{dc}}}{n}\right)^2 = 2.5 U_{\text{dc}} \Delta t_{\text{off}} \cdot i_{\text{fault}}$$

(5)

The turn-off time can be estimated by calculating the time of the capacitor charging.

$$U_c = \frac{i_{\text{fault}} t_r}{C}$$

(6)

Bringing Equation (4) into Equation (6) yields $t_r = 5\Delta t_{\text{off}}$.

The DC power supply voltage $U_{\text{dc}}$ is constant and the current $i_{\text{fault}}$ takes the maximum value. It can be known from Equation (4), (5) and (6) that selecting a IGBT with a larger blocking voltage can reduce the capacitance with little affecting the energy loss and switching time, because $\Delta t_{\text{off}}$ changes little in practical applications.

2.4. Parameters of High Voltage Switching Circuit

A 10kV solid-state DC switching unit based on series-connected IGBTs should be developed to achieve the current interruption of dozens of amps. Under extreme conditions, assuming a trunk current of 10A and a shutdown response time of 50$\mu$s, the maximum fault current at 300km offshore where there is the nearest BU is given by

$$i_{\text{fault}} = i_0 + \frac{U_{\text{dc}} (t_{\mu s} - t_0)}{L_{\text{dc}}} = 10A + \frac{10kV \times 50\mu s}{300km \times 0.4mH / km} = 14.2A$$

(7)

Hence, the specification of five 4kV single tube IGBTs in series (IXEL40N400) is used for the design in consideration of the equipment volume, reliability, fault current and spike voltage during the current interruption. The maximum leakage current of this IGBT is 1.5mA in its datasheet. According to the Equation (1) and (2), resistance $R_S$ in parallel with the IGBT and the power loss on it are 260k$\Omega$ and 75W.

Assuming the time lag is about 1$\mu$s and the fault current is 14.2A calculated by Equation (7), the buffer capacitance and the power loss during each breaking operation can be derived by $\Delta t_{\text{off}} = 1\mu s$ and $i_{\text{fault}} = 14.2A$ as follows $C = 36nF$ and $E_c = 3.6J$ according to the Equation (4) and (5).

The voltage across the series-connected IGBTs is clamped by paralleling an arrester. The energy absorbed in the arrester is given in [10]. The lower the clamp voltage is, the more energy the arrester
needs to absorb. Considering the blocking voltage and arrester selection, the clamp voltage is determined to be 12kV. A ZnO arrester with a maximum clamping voltage of 12kV is adopted.

3. Simulation of High Voltage Power Switching

3.1. Simulation Models of the High Voltage Power Switching

In order to verify the feasibility of the proposed scheme, the power switching when a short circuit fault occurs in CSOs is simulated in the Saber software as shown in Figure 4. A simulation model of the switching unit is established according to the circuit topology proposed in Section 2.2. The PWL resistance model is used to simulate the load and short circuit fault. The parameters of all components of the simulation model are presented in Table 1.

| Part       | Component | Parameter       |
|------------|-----------|-----------------|
| Power system | U_dC     | 10kV            |
|            | L_1      | 80mH            |
|            | L_2      | 40mH            |
| Switching unit | R_s     | 260kΩ           |
|            | C        | 36mF            |
|            | T        | IXEL40N400      |
|            | R_d      | 2.5kΩ           |
|            | Varistor | 1.2kV           |

3.2. Simulation Results with RCD Buffer Circuit

The simulation results are shown in Figure 5. The switch unit is on at 10μs. Since the effect of the inductor, the current rises to a stable operating point at about 800μs. Then the PWL resistance becomes zero imitating a short circuit at t=960μs. After the 50μs switch unit reaction time, the fault current rises to 14.3A. The series-connect IGBTs are shut off near 1010μs slightly asynchronously. The voltage of the switch unit rises steeply, clamped to the preset voltage of 12kV. From the waveform diagram, the IGBTs’ voltage equalizing effect is excellent and the maximum voltage difference is about 320V in case of the RCD circuit, and uneven voltage errors are lower than 10%. It takes about 1200μs to complete a breaking operation.
4. Conclusion
This paper has proposed a HVDC power switching circuit for the BUs of CSOs, based on the voltage sharing scheme of series-connected IGBTs. The circuit can cut off the fault current online instead of decreasing the PFE voltage in the traditional offline approach. The feasibility of the switching unit is verified by both theoretical analysis and computer simulation. The result shows that the switching unit can interrupt the fault current within about 1ms and the voltage balancing among series-connected IGBTs performs well.

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