Operation and transient performance of a four-terminal MMC based DC grid implementing high power mechanical DC circuit breaker

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Abstract: Recently, there has been significant interest in developing the modular multilevel converter (MMC) based DC grids in the power industry. However, the immature DC circuit breaker (DCCB) technology hampers the development of DC grids in overhead lines transmission field. The full controlled power electronic devices based hybrid DCCB has been proposed and researched substantially. But the hybrid type DCCB suffers from the drawback of high cost and low reliability, leading to high operational cost for the DC grid and making the numerous fault currents difficult to control. In this paper, a mechanical type DCCB, consisting of a mechanical switch, a circuit and an oscillation circuit, is proposed. Then, a four-terminal bipolar MMC-HVDC system implementing the mechanical DCCBs is studied. Extensive simulations have been conducted to analyse the transient performance under different fault conditions. The simulation results verify the technical feasibility of this mechanical DCCB in DC grid.

1 Introduction

The modular multilevel converter (MMC) based high voltage direct current (HVDC) transmission systems have developed significantly in recent years. With the progress of the HVDC transmission, it is of interest to use MMC technology to construct the multi-terminal DC (MTDC) system or even the DC grid [1].

Recently, the four-terminal Zhangbei MMC-HVDC transmission project is under construction in China. This project transmits 4500MW wind energy to the load centre using overhead lines [2]. There are many considerable challenges for the operation of this DC grid, one of which is the DC fault management [3–5]. To avoid entire shut-down of the MMC-HVDC transmission system during DC faults, the high power DC circuit breakers (DCCB) are required to isolate the fault lines within few milliseconds, resulting in the difficulty in developing DCCB [6].

Among different topologies of DCCB, the hybrid DCCB proposed by ABB, which consists of an ultrafast mechanical switch and numerous IGBT devices, has been well studied. It transfers the DC fault current to the main branch by controlling the IGBT switches so that the fault energy can be quickly dissipated [7–10]. However, the hybrid DCCB suffers from the drawback of high cost and low reliability. It is essential to propose a more economical and appropriate scheme of DCCB.

This paper proposes a mechanical type DCCB, which consists of a mechanical switch, a series and parallel connected metal oxide varistor (MOV) circuit and an oscillation circuit. The LC oscillation circuit, composed of pre-charged storage capacitor, reactor and thyristor, is to impose a high frequency inverse current on the interrupting fault and create a current zero crossing instantly. Besides, the topology of the forced current zero circuit can use line voltage to charge the storage capacitor for secondary opening after reclosing.

Without the expensive and fragile power electronic devices, the proposed DCCB is able to reduce the cost and improve the reliability. This mechanical DCCB is suitable for the Zhangbei project due to the system’s requirement for large amount of DCCBs. For the DC grid implementing the mechanical DCCB, a preliminary simulation of the system’s operation and transient performance under fault conditions is necessary.

In this paper, the four-terminal bipolar MMC-HVDC system, referring to Zhangbei project, is modelled in PSCAD/EMTDC with implementing the proposed mechanical DCCB. Then, this paper presents the structure of the mechanical DCCB and introduce its operation principle of opening and reclosing. The simulation in different operating scenarios is used to verify the technical feasibility of the mechanical DCCB. The transient performances of three typical faults are investigated and compared, and the comparisons of the transient response under three typical faults conditions are utilised to analyse the fault characteristics of the system.

2 Layout of the four-terminal MMC based DC grid

The structure of the four-terminal MMC-HVDC system is illustrated in Fig. 1. Each converter adopts the half-bridge MMC topology as shown in Fig. 2. The system is designed as master-slave control, where MMC4 is the main control station used to maintain the DC voltage and the other converters are slave stations that control the power of the system. The converters are connected by the meshed network in this system to meet the N-1 principle. Besides, the MMC-HVDC system is a bipolar system, and its circuit is illustrated in Fig. 3. The critical component parameters of the converters in the MMC-HVDC system are given in Table 1, while the parameters of transmission lines are shown in Table 2. In this paper, the power/current is defined as positive flowing from the AC grid to the DC grid.

For bipolar structure, the MMC-HVDC system has three typical faults, including pole-to-neutral-line faults (PNFs), pole-to-pole faults (PPFs) and pole-to-ground faults (PGFs), which are divided into permanent faults and temporary faults, respectively. The fault circuits of the PNF and PPF have a similar distribution of voltage and reactance, except the circuit parameters of the PPF is twice as that of the PNF. Therefore, the fault current of the PNF is nearly equal to that of the PPF at the same fault location. According to the system parameters of the Zhangbei project, the grounding pole, containing a 15Ω resistance, is only installed in the main control station MMC4. Because the fault circuit of the PGF consists of the grounding pole and transmission lines, the fault circuit of the PGF has a greater impedance, and the fault current of the PGF is less than that of the PNF. Therefore, the PNF and PPF are the crucial cases to check the ability of the DCCB.
The MMC-HVDC system adopts the control and protection scheme that the central controller detects the faults and deliver the tripping signals to the specified DCCBs. Since the time for fault detection and signal delivery is fixed, the maximum fault current is related to the rated current, which is the starting point of the increasing current. According to the system parameters shown in Table 1, Line 4 is the main transmission channel of the MMC-HVDC system, which means the rated current on this line is the largest. In this paper, the MMC-HVDC system implementing mechanical DCCB was simulated in the case of the faults occurring on this line to research its operation and transient performance.

### 3 Mechanical DCCB model

The Zhangbei MMC-HVDC project will need 16 DCCBs to clear the DC side faults. The scheme of hybrid DCCB will bring the exorbitant cost of DC breakers, even close to the cost of converters, which are considered to be the most expensive devices in the MMC-HVDC system. This paper proposes a low cost mechanical type DCCB and explains its operation principle. The structure of the mechanical DC breaker is shown in Fig. 4. The mechanical DC breaker consists of a fast mechanical switch (FMS), a series and parallel connected metal oxide varistor (MOV) circuit and a forced current zero circuit (FCZC). The forced current zero circuit, composed of pre-charged storage capacitor, reactor and thyristor, is to impose a high frequency inverse current on the interrupting fault and create a current zero crossing instantly.

#### 3.1 Operation principle of opening

The opening process of the mechanical DCCB is shown in Fig. 5. When a DC fault occurs at \( t = 0 \), the DC current continually increase. After 3 ms of fault detection and communication delay, the DC breaker receives the tripping command, leading to the open of the FMS. After the mechanical time delay of the FMS, the thyristor \( T_1 \) begins to conduct, constructing an LC oscillation circuit, as the red line shown in Fig. 5, then to impose a high frequency inverse current on interrupting fault and create a current zero crossing instantly. The fault current on the mechanical switch is cleared, while the residual current dissipates through the MOV. When the residual fault current completely disappeared, the opening process ended and the fault current has been cleared.

It can be seen from the above analysis that the mechanical time delay is the bottleneck that limits the breaking speed of the mechanical DCCB, which is the same problem for the hybrid DCCB. Therefore, the proposed mechanical DCCB and conventional hybrid DCCB should have a similar breaking time.

#### 3.2 Operation principle of reclosing and reopening

In the previous mechanical DCCB, the pre-charged storage capacitor, used in the forced current zero circuit to generate the pulse current, is difficult to be re-charged quickly before the reclosing due to its relatively large capacitance. Therefore, the mechanical DCCB has the disadvantage of being unable to reopen after reclosing. The topology of the DCCB is improved by adding an auxiliary capacitor. Through the auxiliary capacitor, the forced current zero circuit can use line voltage to charge the storage capacitor for secondary opening.

The reclosing process of the mechanical DCCB is shown in Fig. 6. After the opening process, the storage capacitor \( C_S \) has discharged and its voltage is equal to 0. Meanwhile, the auxiliary capacitor \( C_A \) is charged by the voltage across the DC breaker, through the circuit as the red line shown in Fig. 6a. Since the capacitance of \( C_A \) is less than \( C_S \), the charging speed of \( C_A \) is fast, and the voltage of \( C_A \) will eventually reach \( V_{dc} \). This is the steady state of the DC breaker before reclosing.

Waiting for the deionisation time, the DC breaker starts the process of reclosing. The mechanical switch recloses and the thyristor \( T_2 \) receives a pulse signal, connecting the converter to fault point and recharging the \( C_S \). The red line shown in Fig. 6b indicates the recharging circuit of \( C_S \) after reclosing. Through this
circuit, the $C_S$ will recharge by the discharging of the $C_A$ within 300μs. Due to the unilateral conductivity of the thyristor $T_2$, the $C_S$ is unable to discharge and its voltage will remain for a period of time. If the DC breaker recloses on a temporary fault, the fault has been cleared and the system will return to rated operating state after reclosing. Otherwise, the DC breaker recloses on a permanent fault, causing the continuous increase of the DC current. When the current exceeds the current limit of 6.8 kA, the DC breaker begins to reopen. The reopening process is similar to the opening process.

4 System fault simulation

In this section, the transient performance of the system and the mechanical DCCB is investigated and compared. At 1.5 s, a DC fault is applied at $F_8$ as shown in Fig. 1. Thus, the DCCB8, which is closest to the fault point, is mainly observed in the simulation. The first opening of the DCCBs would happen at 3 ms after the fault occurs. After 300 ms of the deionisation time, the breakers begin to reclose.

4.1 Simulation verification of mechanical DCCB

To prove the capability of this mechanical DCCB, a permanent PNF is applied at the fault point. The storage capacitor is pre-charged to 350 kV. The FMS is modelled as an ideal switch that can only open at the current zero crossing. The responses to the permanent PNF with the mechanical DCCB are shown in Fig. 7.

When the permanent fault occurs, the operating sequence of the system is as follows: 1) at $t_1 = 1.503$ s, the DCCB receives the tripping command, ordering the FMS to open; 2) at $t_2 = 1.5055$ s, the thyristor $T_1$ conducts and storage capacitor discharges to impose an inverse current; 3) at $t_3 = 1.5058$ s, the FMS reaches the current zero crossing and the fault current is broken at 10.31 kA; 4) at $t_4 = 1.5209$ s, the residual current has dissipated through the MOV, causing the absorbed energies achieves 48.83MJ; 5) at $t_5 = 1.803$ s, the FMS is reclosed to the fault and the capacitor voltage $V_c$ is recharged to 342 kV through the conducted $T_2$; 6) at $t_6 = 1.8077$ s, the fault current exceeds 6.8 kA, resulting in the reopening operation of the FMS; 7) at $t_7 = 1.8102$ s, the thyristor $T_1$ conducts again and storage capacitor discharges to impose an inverse current; 8) at $t_8 = 1.8106$ s, the FMS reaches the current zero crossing and the fault current is broken at 10.52 kA; 9) at $t_9 = 1.8255$ s, the residual current has dissipated through the MOV, causing the absorbed energies achieves 95.36MJ.

The response of the MMC-HVDC system is shown in Fig. 8. When a fault occurs at 1.5 s, the DC voltages of all converters decrease rapidly due to the discharge of the sub-module capacitor. After fault clearance, the voltages increase and recover within 200 ms. The voltage response of the reclosing and reopening is similar to the first opening. During the period of the DCCB operation, the voltage is operated in the range of 400 kV to 630 kV (0.74 p.u. to 1.18 p.u.), which is acceptable for a DC grid. These simulation results verify the technical feasibility of the proposed mechanical DCCB.

Table 2 Parameters of the overhead transmission lines

| Parameters                  | Line1 | Line2 | Line3 | Line4 |
|-----------------------------|-------|-------|-------|-------|
| overhead line length        | 49.6 km | 205.1 km | 187.1 km | 206.4 km |
| polar line resistance       | 39.84 mΩ/km |       |       |       |
| neutral line resistance     | 75.2 mΩ/km |       |       |       |

Fig. 4 Mechanical DC breaker structure

Fig. 5 Opening process of the mechanical DCCB

Fig. 6 Reclosing process of the mechanical DCCB

Fig. 7 Response of the mechanical DCCB under permanent PNF scenario

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4.2 Comparison of the performance of three faults

To further study the different faults case and confirm the worst case scenario, the system is simulated under three typical permanent faults. The transient performance of three typical faults is shown in Fig. 9. At the first opening, the fault current of the PNF is almost the same as that of the PPF, while the current of the PGF is obviously less. The maximum current of the PNF, PPF and PGF is 10.31 kA, 10.41 and 8.07 kA, respectively. The breaker voltages in different faults scenario are similar, caused by the characteristics of the arrester. For the reclosing and secondary opening, the maximum current of the PNF, PPF and PGF is 10.521 kA, 10.55 and 9.34 kA, respectively. The fault currents of the PNF and PPF are also the same, while the current rise time of the PGF is more than that of the other faults, due to the slower current rise speed to exceed the current limit. Based on the same reason, the breaker voltage of the PGF is delayed for a few milliseconds.

The energy absorption in different faults scenario is shown in Fig. 10. After the first opening operation, the absorbed energies of the PNF, PPF and PGF are 48.83MJ, 44.66MJ and 27.65MJ, respectively. After the second opening operation, the absorbed energies of the PNF, PPF and PGF reach 95.34MJ, 86.13MJ and 58.04MJ, respectively. Obviously, the PPF has the largest fault current and energy absorption.

Combining the fault current, breaker voltage and energy absorption, the PNF is a little more severe condition due to the largest energy absorption. Furthermore, the failure operation of main protection should be considered to study the worst case scenario. According to the requirement of the Zhangbei project, the backup protection device is installed in the DCCB applied at the other terminal of the transmission line. Under the circumstance of the failure operation of main protection, the backup protection sends the opening command to these DCCBs, which would cost 2 ms to be delivered since the communication delay. For the case of the failure operation of main protection, the opening operation is postponed by 2 ms to model the communication delay of backup protection. Considering the low possibility that the main protections of two DCCBs fail at the same time, only positive DCCB is delayed in the PPF scenario.

The transient performance of three typical faults with main protection failure is shown in Fig. 11. At the first opening, the maximum current of the PNF, PPF and PGF is 12.73 kA, 11.75 and 9.68 kA, respectively. At the second opening, the maximum current of the PNF, PPF and PGF is 10.48 kA, 10.04 and 9.28 kA, respectively. The energy absorption in different faults scenario in case of main protection failure is shown in Fig. 12. After the first opening operation, the absorbed energies of the PNF, PPF and PGF are 64.84MJ, 49.03MJ and 36.5MJ, respectively. After the second opening operation, the absorbed energies of the PNF, PPF and PGF reach 110.6MJ, 85.86MJ and 67.8MJ, respectively. Obviously, the PPF has the largest fault current and energy absorption.

Through the above simulations of fault current, breaker voltage and energy absorption, the PNF is the most severe case scenario, especially with main protection failure.

5 Conclusions

In this paper, an economical mechanical type DCCB is proposed and its operation principle is introduced. This mechanical DCCB use the discharge of the pre-charged storage capacitor to impose high frequency inverse current on interrupting fault current. It can also utilise line voltage to recharge the storage capacitor for secondary opening after reclosing. The four-terminal bipolar MMC-HVDC system with the proposed mechanical DCCB is simulated under different fault scenarios. The simulation results show that the mechanical DCCB breaks the fault current within 6 ms and has the ability to reopen after reclosing. That verifies the technical practicability of the mechanical DCCB. Comparison of the transient performances under three typical faults demonstrates the PNF is the worst fault case scenario.

Fig. 8 DC voltages of the MMC-HVDC system under permanent PNF scenario

Fig. 9 Transient performance under different faults scenarios

Fig. 10 Energy absorption under different faults scenarios

Fig. 11 Transient performance with main protection failure

Fig. 12 Energy absorption with main protection failure

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