Review of hybrid HVDC systems combining line communicated converter and voltage source converter

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Abstract

Hybrid HVDC system, which consists of the advantages of line commutated converter (LCC) and voltage source converter (VSC), is an emerging power transmission system. This paper presents a review of four LCC-VSC hybrid HVDC topologies. The first topology is the pole-hybrid HVDC system, in which the LCC and VSC form the positive- and negative-pole respectively. The second one is the terminal-hybrid HVDC system; in this topology one terminal adopts LCC and the other terminal adopts VSC. The series converter-hybrid HVDC system is the third topology wherein each terminal is formed by LCC and VSC in series. The fourth hybrid topology under consideration is a parallel converter-hybrid HVDC system with LCC and VSC connected in parallel in each ter- minal. The main contribution of this paper is a comprehensive analysis and comparison of the four mentioned hybrid topologies in terms of PQ operating zone, power flow reversal method, and DC fault ride-through strategy.

Keywords

Hybrid HVDC system; Line commutated converter ; Voltage source converter; PQ operating zone; Power flow reversal; DC fault ride-through

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Introduction

High voltage direct current (HVDC) system is widely used in long- distance bulk-power transmission [1]. In general, there are two HVDC converters [2,3]: line commutated converter (LCC) and voltage source converter (VSC).

Since the first commercial HVDC project (Gotland HVDC link) was put into operation in 1954, the LCC-HVDC technology has been devel- oped for over sixty years [4]. The LCC-HVDC systems have been widely used for bulk power transmission over long distance connecting remote generation sources to load areas. So far, the power rating of LCC-HVDC is as high as 10 GW [5]. However, the thyristors used in LCC can only be turned on, their turn-off relies on the grid voltage. This drawback makes the LCC unable to connect to the passive network or even a weak AC system. The LCC inverter may suffer commutation failure during AC faults. Moreover, the LCC-HVDC consumes a large amount of reactivepower while transmitting active power.

As an alternative, the VSC-HVDC technology was put forward around 1990 [6,7]. VSC is made with switching devices (e.g. IGBT) that can be turned both on and off. The commutation of VSC is performed independently of the grid voltage, which makes it possible to control reactive power independent of regulating active power. As a result, no commutation failure may occur, and the very weak AC system can be supplied with power using VSC-HVDC [8]. With recent technology advancements, VSC-HVDC can now be used for power transmission at ultra-high voltages up to 800 kV [9]. However, compared to LCC-HVDC, VSC- HVDC has the disadvantages of higher installation cost, smaller power rating, and higher loss in most cases [10].

LCC and VSC can be incorporated into a hybrid HVDC system which combines the advantages of both converters. Reference [11] discusses four hybrid topologies in terms of dimensioning and PQ capability. These topologies are mainly at the converter level. For system level topologies, hybrid HVDC system can be divided into four types: 1) pole- hybrid system, 2) terminal-hybrid system, 3) series converter-hybrid system, 4) parallel converter-hybrid system.

A pole-hybrid HVDC system is a bipolar system that one pole adopts LCC-HVDC and the other pole uses VSC-HVDC. A typical pole-hybrid HVDC project is the Skagerrak HVDC system [12]. This HVDC system connects the hydroelectric-based Norwegian grid and the wind and thermal power-based Danish grid, as shown in Fig. 1(a). In this system, Skagerrak 3 is a LCC-based HVDC link and Skagerrak 4 is a VSC-based HVDC link. They are tied together in a bipolar configuration which forms a pole-hybrid HVDC system. In normal operation, the system enables both grids to add more renewable energy to their energy mix, and to use electricity more efficiently. In the case of the outage of either power grid, a fast restoration can be achieved due to the technology's black start capability.

In a terminal-hybrid HVDC system, one terminal adopts LCC and the other terminal adopts VSC [13–17]. Fig. 1(b) shows a terminal-hybrid HVDC system called Wudongde HVDC project [9]. This project is a three-terminal hybrid HVDC system that transmitting clean and cheap hydropower of Yunnan (YN) Province to the load center of Guangxi (GX) and Guangdong (GD) Province. The terminal at YN is an 8000 MW LCC station. Other two terminals are 3000 MW (GX) and 5000 MW (GD) VSC stations. The overhead transmission line is about 1500 km. This project helps to further integrate the renewable energy in YN, and ensure the power supply in GX and GD without commutation failure.

Converter-hybrid HVDC system uses converters that are formed with LCC and VSC. According to the connection methods of LCC and VSC, the converter-hybrid HVDC system can be divided into series converter- hybrid HVDC and parallel converter-hybrid HVDC [18–23]. A series converter-hybrid HVDC project called Baihetan-Jiangsu (BHT-JS) HVDC is under planning [24]. This project aims to deliver the hydropower of BHT to JS which is shown in Fig. 1(c). The receiving end in JS adopts the series converter-hybrid HVDC technology. Part of the reactive power consumed by LCC is supplied by VSC. The grid stability of JS can be improved due to the AC voltage support capability of VSC. As for the parallel converter-hybrid HVDC, there are a few studies in the literature reporting this system [21–23]. The two different HVDC converters are connected to the same DC line. Transmission corridor is saved as onlyone HVDC transmission line is needed. Up till now, no related project is under construction or planning.

In this paper, a comprehensive review of the four hybrid HVDC systems mentioned above is studied, i.e., pole-hybrid HVDC system, terminal-hybrid HVDC system, series converter-hybrid HVDC system, and parallel converter-hybrid HVDC system. The analysis and comparison are carried out in terms of PQ operating zone, power flow reversal method, and DC fault ride-through strategy. To the best knowledge ofthe authors, such a comprehensive analysis and comparison has not been presented before.

The paper is organized as follows. The basic topologies of the four hybrid HVDC systems are introduced in Section 2. The PQ operating zones are analyzed in Section 3. Section 4 discusses the power flow reversal methods for the four topologies. DC fault ride-through methods of different hybrid HVDC systems are compared in Section 5. Finally,Section 6 concludes the paper.

Basic Topologies of Four Hybrid HVDC Systems

This section briefly describes the basic topologies of the four hybrid HVDC systems. The topologies discussed in this paper are the general ones and might be a little different from those in practical projects.

2.1 Pole-hybrid HVDC System

Fig. 2 shows the basic topology of the pole-hybrid HVDC system (PH). One pole is a LCC-HVDC link. The other pole is a VSC-HVDC link. The PH topology is asymmetric, so both DC currents and voltages of LCC and VSC can be different. In normal operation, DC currents of the two links are controlled to the same value so as to minimize earth current. The absolute values of their DC voltages can be different so that power delivered by each link might be different. The PH topology can be used to upgrade the existing monopolar LCC-HVDC to improve system control flexibility.

2.2 Terminal-hybrid HVDC System

Fig. 3 illustrates the basic topology of the terminal-hybrid HVDC system (TH). In this system, one terminal adopts LCC and the other terminal uses VSC. The VSC terminal can operate in rectifier or inverter mode. The system with VSC working as rectifier is mainly used for wind power integration because the VSC can be controlled as a grid-forming converter. When the VSC terminal operates in the inverter mode, no commutation failure will occur in the receiving end. This advantage makes it a good solution to transmit power to the load centers with low short circuit ratio (SCR). As for a two-terminal system, the LCC and VSC in the TH topology have the same DC current and voltage, so their power ratings are the same. But in a multi-terminal system, their power ratings can be different.

2.3 Series Converter-hybrid HVDC System

Fig. 4 shows the basic topology of the series converter-hybrid HVDC system (SCH). The positive and negative poles are symmetric. Each terminal is formed by LCC and VSC in series. Thus, the current flowing through the LCC and VSC is exactly the same, but their DC voltage can be different. Therefore, the ratio of the transmitted power of LCC over VSC equals to the ratio of their DC voltages. This topology is able to supply power for the weak AC grid because there is VSC in the converters. Besides, with cooperative control of LCC and VSC, the current cut-off will not occur under AC faults at the sending system.

2.4 Parallel Converter-hybrid HVDC System

Fig. 5 is the basic topology of the parallel converter-hybrid HVDC system (PCH). Each terminal consists of one LCC and one VSC. The two different HVDC converters are connected in parallel to the same DC line. Thus, their DC voltages are the same. The DC currents flowing through the LCC and VSC are different so that their transmitted power can be different. After the shutdown of either system can still continue to transmit power.

PQ Operating Zone

This section compares the PQ operating zones of the four topologies under consideration. The PQ operating zone is the set of all possible operating points of active (P) and reactive (Q) power. According to the studies in [21,25,26], the current constraint plays a major role in the calculation of PQ operating points in normal operation. Thus, the PQ operating based on the current constraint.

3.1 Terminal-hybrid HVDC System

In TH topology, one terminal is LCC and the other terminal is VSC. The PQ operating zones of these two terminal can be derived as follows.

(1) LCC Terminal

The DC voltage of LCC depends on the firing angle α of the thyristor valves according to (1)

$$V_{\mathrm{dcLCC}} = V_{\mathrm{dc0}} cos\alpha - d_x I_{\mathrm{dcLCC}} \quad (1)$$

where V_{dcLCC} and I_{dcLCC} represent the DC voltage and current of LCC, V_{dc0} is the ideal DC voltage for firing angle $\alpha = 0^{\circ}$ and d_x is the equiv- alent impedance [2]. The expressions of V_{dc0} and d_x can be written as

$$V_{\mathrm{dc0}} = \frac{3\sqrt{6}}{\pi T} V_{\mathrm{ac}} \quad (2)$$

$$d_x = \frac{3X_C}{\pi} \quad (3)$$

where V_{ac} is the phase voltage of the AC system, T is the transformer turns ratio, and X_{C} is the commutation impedance per phase.

The active power and the corresponding reactive power demand of CC are given by

$$P_{\mathrm{LCC}} = (V_{\mathrm{dc0}} cos\alpha - d_x I_{\mathrm{dcLCC}}) I_{\mathrm{dcLCC}} \quad (4)$$

$$Q_{\mathrm{LCC}} = V_{\mathrm{dc0}} I_{\mathrm{dcLCC}} \sqrt{1 - \left(cos\alpha - \frac{d_x I_{\mathrm{dcLCC}}}{V_{\mathrm{dc0}}}\right)^2} \quad (5)$$

According to (4) and (5), the PQ operating zone of the LCC terminal is illustrated in Fig. 6(a). The LCC needs to consume a large amount of reactive power while transmitting active power. When fixing the DC voltage (V_{dcLCC}), the increase of the DC current (I_{dcLCC}) results in the increase of both active power and reactive power demand. On the other hand, if the DC current is fixed, increasing the DC voltage leads to the increase of active power and the decrease of reactive power demand. Thus, if we want to reduce the transmitted power, it is better to decrease rent instead of the DC voltage.

In the dq-axis synchronous frame, the mathematical model of VSC can be given by the following equations [10,27]

$$L\frac{\mathrm{d}i_{\mathrm{vd}}}{\mathrm{d}t} + Ri_{\mathrm{vd}} = u_{\mathrm{vd}} - u_{\mathrm{sd}} + \omega L i_{\mathrm{vq}} \quad (6)$$

$$L\frac{\mathrm{d}i_{\mathrm{vq}}}{\mathrm{d}t} + Ri_{\mathrm{vq}} = u_{\mathrm{vq}} - u_{\mathrm{sq}} - \omega L i_{\mathrm{vd}} \quad (7)$$

where i_{vd} and i_{vq} are output currents in dq-axis synchronous frame; u_{vd} and u_{vq} are output voltages; u_{sd} and u_{sq} are AC system voltages; L and R are equivalent inductance and resistance in the AC side. ω is the angular is is aligned with AC system e and reactive power of VSC can be expressed as

$$P_{\mathrm{VSC}} = 1.5 u_{\mathrm{sd}} i_{\mathrm{vd}} \quad (8)$$

$$Q_{\mathrm{VSC}} = -1.5 u_{\mathrm{sd}} i_{\mathrm{vq}} \quad (9)$$

As the d-axis is aligned with AC system voltage, so u_{sd} equals to the amplitude of AC system voltage and u_{sq} is zero. In this way, the active and reactive power of the VSC can be independently controlled by regulating i_{vd} and i_{vq}. Due to the limitation of VSC power rating, the output currents should meet the following constraint

$$i_{\mathrm{vd}}^2 + i_{\mathrm{vq}}^2 \leqslant 1 \text{ p.u.} \quad (10)$$

3.2 Pole-hybrid HVDC

The phasor diagram of the PH topology is shown in Fig. 7. Grid voltage of phase a V_{sa} is selected as the reference with angle equal to zero. The current flowing through phase a of LCC I_{aLCC} lags V_{sa} with its power angle φ_1. Angel φ_2 is the phase difference between the VSC cur- rent I_{aVSC} and the grid voltage V_{sa} so that the power factor of the VSC can be defined by angle φ_2. It should be noted that I_{aVSC} can be in any quadrant as the active and reactive power of the VSC are controlled independently. I_{sa} is the grid current and angle φ is the power angle of the PH topology. The grid current can be calculated by summing the x- and y-a nd the VSC current as follows:

$$I_{\mathrm{sa}} cos\varphi = I_{\mathrm{aVSC}} cos\varphi_2 + I_{\mathrm{aLCC}} cos\varphi_1 \quad (11)$$

$$I_{\mathrm{sa}} sin\varphi = I_{\mathrm{aVSC}} sin\varphi_2 - I_{\mathrm{aLCC}} sin\varphi_1 \quad (12)$$

Summing he squares of (11) and (12) yields

$$I_{\mathrm{sa}}^2 = (I_{\mathrm{aVSC}} cos\varphi_2 + I_{\mathrm{aLCC}} cos\varphi_1)^2 + (I_{\mathrm{aVSC}} sin\varphi_2 - I_{\mathrm{aLCC}} sin\varphi_1)^2 \quad (13)$$

Therefore, the operating points of the PH topology can be described by the following equation:

$$P^2 + Q^2 = S^2 = \left(\frac{3}{2}V_{sa}I_{sa}\right)^2 = \left(\frac{3}{2}V_{sa}\right)^2 I_{sa}^2 \\ = (P_{VSC} + P_{LCC})^2 + (Q_{VSC} - Q_{LCC})^2 \tag{14}$$

It can be seen from (14) that the active power (P) of the PH topology is the sum of VSC (P_{VSC}) and LCC (P_{LCC}), but the reactive power (Q) equals to the reactive power generated by the VSC (Q_{VSC}) minus the reactive power absorbed by the LCC (Q_{LCC}). It implies that part or all of the LCC reactive power consumption can be compensated by the VSC. Besides, both the active and reactive power of the PH topology can be regulated without altering the operating point of the LCC. That is to say the LCC can operate at a fix operating point with minimum reactive power consumption, while the active power of the PH topology can be controlled by the VSC. Thus, the operating of the PH topology is very flexible.

In order to analyze the PQ operating zone, the power ratio k is d as the ratio of VSC rated power to LCC rated power which is given by

$$k = \frac{P_{VSC}}{P_{LCC}} \tag{15}$$

According to (14) and (15), the PQ operating zone of the PH topology is illustrated in Fig. 8 with a different value of k. From the analysis above we know that the operating points of the LCC and VSC are independent of each other. Thus, the PQ operating zone of the PH topology can be obtained by moving the center of the VSC circular area along the LCC PQ operating points. As seen from Fig. 8, the larger t k is, the closer the extended PQ area is to an ideal circle.

3.3 Series converter-hybrid HVDC System

The SCH topology has the same phasor diagram as the PH topology shown in Fig. 7. Thus, the calculation process of PQ operating zone is similar to that in the above section. But an additional constraint needs to be considered for the SCH topology. That is, the DC current flowing through the LCC and the VSC is the same

$$I_{dcLCC} = I_{dcVSC} = I_{dc} \tag{16}$$

Inserting (16) to (15), the power ratio can be rewritten as

$$k = \frac{P_{VSC}}{P_{LCC}} = \frac{V_{dcVSC}I_{dcVSC}}{V_{dcLCC}I_{dcLCC}} = \frac{V_{dcVSC}}{V_{dcLCC}} \tag{17}$$

Thus, the ratio of transmitted power of LCC over VSC equals to the ratio of their DC voltages.

According to (14), (16) and (17), the PQ operating zone of the SCH topology can be presented in Fig. 9. For a given LCC operating point, the active power of the VSC is calculated by $P_{VSC} = k \times P_{LCC}$. Then maximum reactive power is obtained with constraint $P_{VSC}^2 + Q_{VSC}^2 \leq (k/(1+k))^2$ pu.

3.4 Parallel Converter-hybrid HVDC System

Similarly, the PQ operating zone of the PCH topology can also be derived with the same phasor diagram shown in Fig. 7. Different from the SCH topology, the DC currents of the LCC and the VSC in the PCH topolog r DC voltage is the same. That is

$$V_{dcLCC} = V_{dcVSC} = V_{dc} \tag{18}$$

In this way, the power ratio is given by

$$k = \frac{P_{VSC}}{P_{LCC}} = \frac{V_{dcVSC}I_{dcVSC}}{V_{dcLCC}I_{dcLCC}} = \frac{I_{dcVSC}}{I_{dcLCC}} \tag{19}$$

Thus, the ratio of transmitted power of LCC over VSC equals to the ratio of their DC currents.

According to (14), (18) and (19), the PQ operating zone of the PCH topology is shown in Fig. 10. The PQ operating zone of the PCH topology can be obtained by moving the center of the VSC circular area along the LCC PQ operating points. It should be noted that when the system is in bulk operation, there is a limitation for the active power of the VSC as

$$P_{\mathrm{VSC}} = V_{\mathrm{dc}} I_{\mathrm{dc}} \leqslant V_{\mathrm{dc}} I_{\mathrm{dcnVSC}} \tag{20}$$

where I_{dcnVSC} is the rated DC current of VSC. Therefore, under this condition the VSC operating zone is part of the circular a the active power not exceeding its maximum value $V_{\mathrm{dc}} I_{\mathrm{dcnVSC}}$.

3.5 Discussion

The comparison of the four hybrid HVDC systems in terms of PQ operating zone is listed in Table 1. For the TH topology, the PQ operating zone of the LCC terminal is in the third and fourth quadrants, which means it needs reactive power compensation while transmitting active power. In addition, the reactive power cannot be independently controlled with active power. In contrast, The PQ operating zone of the VSC terminal is a circular area. Its active and reactive power can be controlled independently. For the other three topologies, the PQ operating zone is the combination of the LCC and VSC. Even with a small value of power ratio k (e.g. k = 1/3), these three topologies can provide capacitive reactive power for the AC grid while transmitting active power. This characteristic can be recognized as partially independent control of active and reactive power. As for the converter power rating, the LCC terminal and VSC terminal in the TH topology are the same because the sent and received power are always balanced in normal operation. While for the other three topologies, the power ratings of LCC and VSC can be different. The larger the power ratio k is, the closer the combined PQ area is to an ideal circle. Therefore, the capital cost of the PH, SCH and PCH topologies are more flexible. For example, the power rating of VSC can be designed to low value while keeping the bulk-power transmission capability of LCC to achieve relatively low capital cost. The PQ operating zone of the SCH topology is smaller than that of the PH topology, because the DC current flowing through the LCC and VSC in the former should be the same. The PCH topology has the same operating zone as the PH topology, even though the DC voltages of LCC and VSC in the PCH topology need to be the same.

Power Flow Reversal Method

In many cases, the exchanged power between the two ends is bidictional. That means the hybrid HVDC systems need to be equipped with power flow reversal control. This section mainly discusses the power flow reversals of the four topologies.

In a LCC link the DC current always flows in the same direction, and the power flow reversal is achieved by changing the DC voltage polarity. For most of the VSC converters, the DC voltage polarity is fixed, the power direction can be reversed by changing the DC current direction. However, when the LCC and VSC form a hybrid HVDC system, additional measures are required to realize the power flow reversal.

One of the effective way to change the power direction is using the reversal switch [28]. As shown in Fig. 11, the power reversal switch consists of six mechanical switches. When S_{P1}, S_{N1}, S_{P2} and S_{N2} are closed and S_{P3} and S_{N3} are opened, the DC line current is in positive direction [see Fig. 11(a)]. After receiving the power reversal commend, S_{P1} and S_{N1} are opened to disconnect the converter [see Fig. 11(b)]. Then S_{P2}, S_{N2} are switched off and S_{P3}, S_{N3} are switched on [see Fig. 11 (c)]. Finally S_{P1} and S_{N1} are reclosed so that the DC line current is in negative direction [see Fig. 11(d)]. The reversal switch can be implemented in the DC side of LCC to change the current direction of DC lines, or of VSC to change the voltage polarity.

The voltage polarity of a VSC can also be reversed by adopting full- bridge modular multilevel converter (FB-MMC). Fig. 12 shows the structure of a FB-MMC. The output voltage of a sub-module (SM) in the FB-MMC can be positive, zero and negative. Thus, the FB-MMC can regulate the DC voltage ay, the power di- rection can be changed.

4.1 Pole-hybrid HVDC System

For the PH topology, both the reversal switch and FB-MMC can be used to realize the power flow reversal. In the Skagerrak HVDC project, two reversal switches are installed in the DC side of the VSC link to change polarity from + 500 kV on the DC cable to - 500 kV [12]. The polarity reversal can also be done by adopting FB-MMC. However, both two methods only change the power direction of the VSC link. The power flow reversal of the LCC link can be done by shutting down the LCCs, changing control mode and restarting the , earth current will occur during the power flow reversal.

4.2 Terminal-hybrid HVDC System

When the reversal switch is used to achieve power flow reversal for the TH topology, the whole HVDC system is required to stop operation first. After changing the connection points of the LCC or VSC, system restart is performed and the power direction is changed.

When the VSC terminal adopts FB-MMC, there is no need to shut down the LCC or VSC during power flow reversal. The process of changing power direction is as follows:

- Initially, the FB-MMC controls DC voltage and the LCC regulates DC current.
- Keep the DC current of LCC to a reasonable value. The reason of this step is that maintaining a certain current helps speed up the power flow reversal.
- Adjust the voltage reference of FB-MMC from 1 pu to 1 pu linearly. In this way the voltage polarity eversed, thus the power flow is also reversed.

4.3 Series Converter-hybrid HVDC System

There are two ways to realize power flow reversal for the SCH topology. By installing the reversal switch in the DC side of each LCC, the DC current direction can be changed. Another way is to change the voltage polarity. This can be done by adopting FB-MMC or using the reversal switch in the n and restart are required for both ways.

4.4 Parallel Converter-hybrid System

In the PCH topology, the LCC and VSC are connected in parallel in each terminal. So when the LCCs are disconnected by the reversal switches, the remaining part is a VSC link. Then the power direction can be easily reversed by changing the DC current. During this period, the connecting points of LCCs are reversed by the reversal switches. After that the LCCs is reconnected to the system. Similar to the PH topology, the shutdown is required for the LCCs. But there is no earth current for the PCH topology during the power flow reversal.

Adopting FB-MMC is another solution. Due to the flexible control of FB-MMC, the PCH topology could perform power flow reversal without shutdown of either LCCs or FB-MMCs [21]. The sequence of power flow reversal is as follows:

- Reduce the active power of two FB-MMCs to zero.
- Keep the DC current of LCCs to a reasonable value.
- Adjust the voltage reference of FB-MMC from 1 pu to -1 pu linearly. Because the LCC and FB-MMC are connected to the same DC lines, the DC voltage of LCC is also changed.
- Increase the transmitted power to the desired level by adjusting DC current reference of LCC and active power of FB-MMC.

4.5 Discussion

The power flow reversals of the four hybrid HVDC systems can be done by installing a reversal switch or adopting FB-MMC. Their com- parison results can be seen in Table 2.

When using the reversal switch, the TH and SCH topologies need to stop the operation of the whole HVDC system. This may lead to power interruption for a while. Whereas the PH and PCH topologies only need to shut down the LCCs. The difference between the PH and PCH topologies is that during power reversal there is no earth current in the latter system.

Adopting FB-MMC is an alternative method. The SCH topology still needs system shutdown with the FB-MMC. For the PH topology, the shutdown is only required for the LCCs. While for the TH and PCH topologies, both FB-MMCs and LCCs could operate continuously during the whole process of power flow reversal.

If the power flow reversal does not need to be performed frequently, installing the reversal switch is a good choice due to its low capital cost. Otherwise, it is suggested to adopt FB-MMC, especially for the TH and PCH topologies.

DC Fault Ride-Through Strategy

When overhead lines are used in the HVDC systems, DC faults will occur frequently due to lightening strikes [29]. DC fault ride-through strategy needs to be considered in these situations. Generally, there are three main methods to clear DC faults: 1) tripping AC circuit breaker (ACCB), 2) tripping DC circuit breaker (DCCB), and 3) adopting fault-blocking converter [30–32].

The first method is the most economical and commonly used way in commercial projects. But the response of the ACCB is slow (typically 60–100 ms), which takes a long time for the system to recover from the DC faults. Employing DCCB is another alternative. The operating time of the DCCB is in the range 1 ms to 10 ms, which is far shorter than the ACCB. But the DCCB is of high capital cost and is still lack of practical operation experience, especially for high voltage applications. Adopting fault-blocking converter is the third method to handle DC faults. The operating speed is as fast as the DCCB and is a good substitution for the DCCB in point-to-point applications. Fault-blocking converters include MMC with clamp double sub-module (C-MMC), full-bridge sub-module (FB-MMC) and so on. LCC is also a fault-blocking converter which can clear DC faults by force retardation of its firing angle.

This section discusses the DC fault ride-through strategy of the four hybrid HVDC systems with the above methods that only suitable for the specific topology.

5.1 Pole-hybrid HVDC system

For the PH topology, if a pole-to-ground (PTG) fault is placed at the DC line of the LCC link, the fault can be blocked by applying force retardation of LCCs. If the PTG fault occurs at the DC line of the VSC link, one of the three methods mentioned above is required to clear the fault. Because the LCC and VSC links are in different poles, the PTG fault in one pole will not affect the operation of the other pole.

When a pole-to-pole (PTP) fault occurs, the LCC and VSC in one terminal are connected in series in the fault current path as shown in Fig. 13(a). After applying the force retardation of the LCC, the equivalent circuit is illustrated in Fig. 13(b). If the back electromotive force (EMF) generated by the LCC (V_{FLCC}) is larger than the maximum DC voltage of VSC after blocking (V_{FVSC}), the fault current can be effectively restricted

$$V_{FLCC} > V_{FVSC} \tag{21}$$

The back EMF of LCC after force retardation is given by [18]

$$V_{FLCC} = \left| \frac{cos\alpha_F}{cos\alpha_N} V_{dcLCC} \right| \tag{22}$$

where α_N and V_{dcLCC} are the firing angle and DC voltage of LCC in normal operation, α_F is the firing angle of LCC after retardation. The maximum voltage of VSC after blocking is

$$V_{FVSC} = \sqrt{2}E \tag{23}$$

where E is the RMS value of AC voltage in the converter side. The ionship of E and V_{dcVSC} (i.e. DC voltage of VSC in normal operation) is [33]

$$E = (1.00\ 1.05)\frac{V_{dcVSC}}{2} \tag{24}$$

$$k = \frac{V_{dcVSC}}{V_{dcLCC}} < \sqrt{2}\left|\frac{cos\alpha_F}{cos\alpha_N}\right| \tag{25}$$

Usually, the firing angle of the rectifier LCC is 15° under steady state. It is easy to get $k < 1.04$ when $\alpha_F = 135°$, and $k < 1.27$ when $\alpha_F = 150°$. Therefore, if we want to use LCC to clear the PTP fault of the PH topology, the DC voltage ratio of the LCC and VSC should satisfy the constraint in (25).

5.2 Terminal-hybrid HVDC System

For TH topology, the LCC terminal and VSC terminal need to clear DC faults separately. It is easy for the LCC terminal to block DC fault current since LCC itself is a fault-blocking converter. Whereas the VSC terminal needs to utilize one of the above three methods to handle DC faults.

For this specific topology, another effective solution to ride-through the DC faults is to install diodes on the overhead lines close to the VSC terminal [14], as shown in Fig. 14(a). When DC fault occurs, the current feeding from VSC can be blocked by the diodes. A bypass switch can be connected in parallel with the diodes in case the system needs to change the power direction. In fact, the diodes can also be installed on the low- voltage side of each VSC, as shown in Fig. 14(b). In this way, the potential of the diodes in normal operation is reduced to almost zero.

5.3 Series Converter-hybrid HVDC System

The DC fault clearance method of the SCH topology is similar to the PTP fault ride-through strategy of the PH topology mentioned in Section 5.1. That is, when the constraint (25) is met, the force retardation of LCC can be used to cut off the fault current.

5.4 Parallel Converter-hybrid HVDC System

Different from the SCH topology, the LCC and VSC in the PCH topology are connected in parallel. Each converter needs to block its own fault current. The LCC can handle the DC faults with force retardation. For the VSC, tripping ACCB, tripping DCCB or adopting fault-blocking converter is required to cut off fault current.

5.5 Discussion

The comparison of the four hybrid HVDC systems in terms of DC fault ride-through strategy is shown in Table 3.

Among the four topologies, the SCH noe can ride-through DC faults with only LCC force retardation when the DC voltage ration of VSC and LCC satisfies the constraint in (25). So there is no extra device or control action required.

For the other three topologies, both LCC and VSC need to cut off the fault current independently. The LCC can block the current with force retardation, while the VSC can trip ACCB, trip DCCB or use the fault- blocking converter to clear DC faults.

Due to the special structure of the TH topology, installing diodes on the DC lines or on the low-voltage side also be an effective DC fault ride-through method.

Overall Comparison

The over all comparison of the four hybrid HVDC systems is presented in Table 4. More stars in the cell means better performance in the cor- responding field.

Generally, the PH topology is mainly used to upgrade the existing monopolar LCC-HVDC to improve system control flexibility. The TH and SCH topologies are good options for large capacity transmission scenarios without power flow reversal, such as the west-to-east (source to load centre) power transmission in China. Whereas the PCH topology is suitable for bidirectional large capacity transmission scenarios, such as the cross-seam North American interconnections.

Conclusion

This paper presents a review of four LCC-VSC hybrid HVDC systems in terms of PQ operating zone, power flow reversal method, and DC fault ride-through strategy.

In the PH topology, one pole is a LCC-HVDC link, and the other pole is a VSC-HVDC link. The DC voltage and current of LCC and VSC can be different. But earth current appears when their DC currents are not the same. The PQ operating zone of pH topology is the combination of the LCC and VSC. Even with small value of power ratio k (e.g. k 1/3), the PH topology can provide capacitive reactive power for the AC grid while transmitting active power. When performing power flow reversal, the LCC link needs to be shut down. To handle DC faults, the LCC link can block the current with force retardation, while the VSC link needs to trip ACCB, trip DCCB or use fault-blocking converter.

The TH topology uses LCC in one terminal and VSC in the other terminal. The LCC terminal has the same DC voltage and current as the VSC terminal, so their converter power ratings are the same. Due to the special structure of the TH topology, installing diodes on the DC lines or on the low-voltage side of the VSC could be an effective method to ride- through DC faults. Besides, if the full-bridge MMC is used in the VSC terminal, the TH topology can achieve power flow reversal without stopping the operation of either LCC or VSC.

The LCC and VSC in the SCH topology are connected in series, so the DC currents flowing through them are the same. With this DC current constraint, its PQ operating zone is a little smaller than the PH topology. As for power flow reversal, the SCH topology needs to shut down both LCC and VSC, which will lead to power interruption for a while. When the DC voltage ratio of VSC and LCC satisfies the constraint in (25), the SCH topology can ride-through DC faults with only LCC force retardation.

As for the PCH topology, the LCC and VSC in each terminal are connected in parallel. Due to the parallel connection, the bulk-power transmission capability of LCC can be achieved while keeping a low power rating of VSC. The PCH topology has the same operating zone as the PH topology, even though the DC voltages of LCC and VSC in the PCH topology need to be the same. With the coordination control of LCC and full-bridge MMC, the PHC topology could perform power flow reversal without stopping system operation. Under DC faults, the LCC and VSC in the PCH topology are require to cut off their own fault currents, respectively.

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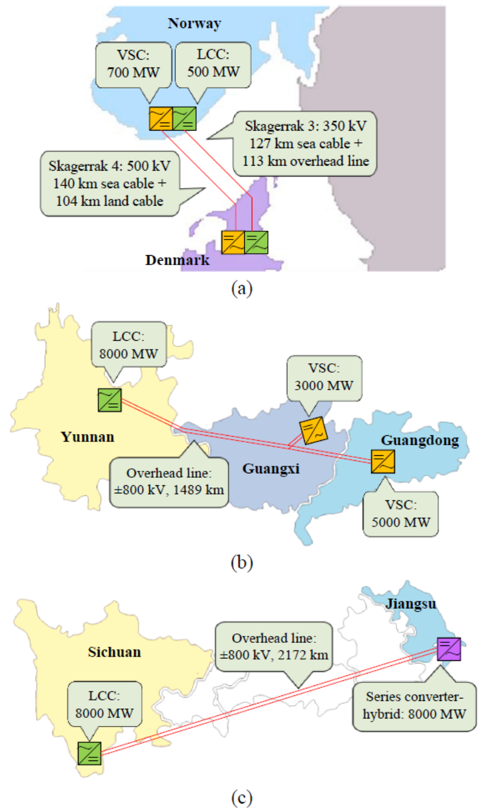

Fig. 1. Three hybrid HVDC projects. (a) Skagerrak pole-hybrid HVDC. (b) Wudongde terminal-hybrid HVDC. (c) Baihetan-Jiangsu series converter-hybrid HVDC.

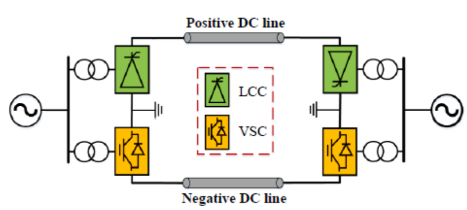

Fig. 2. Basic topology of the pole-hybrid HVDC system (PH).

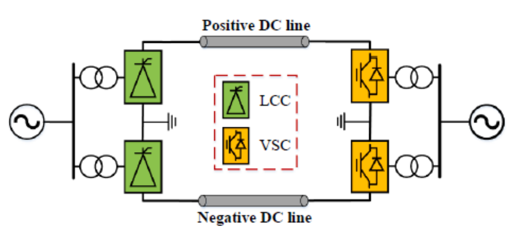

Fig. 3. Basic topology of the terminal-hybrid HVDC system (TH).

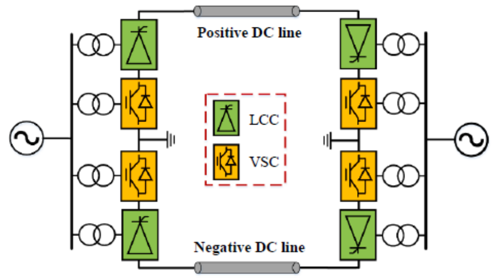

Fig. 4. Basic topology of the series converter-hybrid HVDC system (SCH).

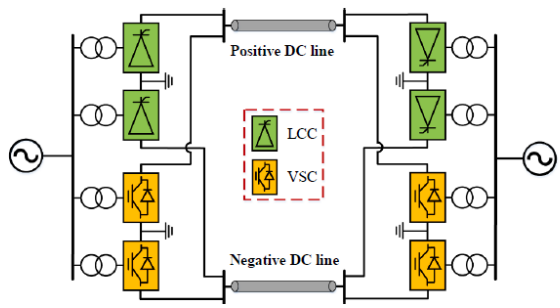

Fig. 5. Basic topology of the parallel converter-hybrid HVDC system (PCH).

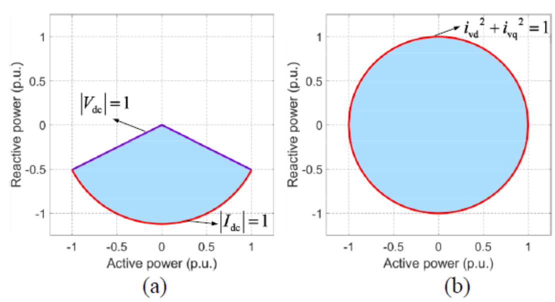

Fig. 6. PQ operating zone of the terminal-hybrid HVDC system. (a) LCC terminal. (b) VSC terminal.

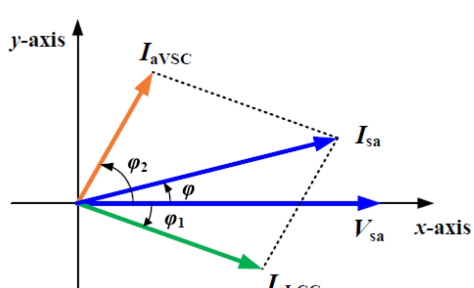

Fig. 7. Phasor diagram of the pole-hybrid HVDC system.

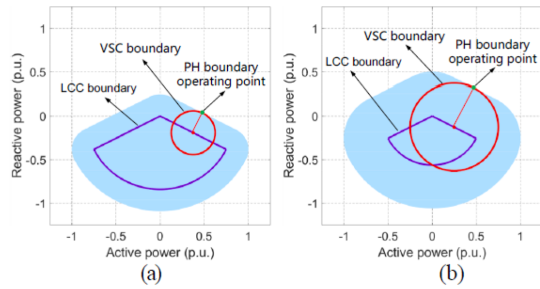

Fig. 8. PQ operating zone of the pole-hybrid HVDC system. (a) With $k = 1/3$. (b) With $k = 1$.

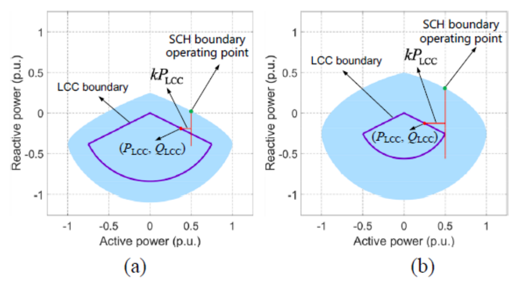

Fig. 9. PQ operating zone of the series converter-hybrid HVDC system. (a) With $k = 1/3$. (b) With $k = 1$.

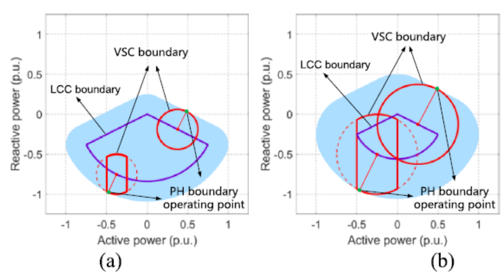

Fig. 10. PQ operating zone of the parallel converter-hybrid HVDC system. (a) With $k = 1/3$. (b) With $k = 1$.

Table 1
Comparison of PQ operating zone.

Items	PH topology	TH topology	SCH topology	PCH topology
DC voltage of LCC and VSC	Different	Same	Different	Same
DC current of LCC and VSC	Can be different, usually the same	Same for two-terminal	Same	Different
PQ operating zone	The combination of the LCC and VSC.	LCC is in the third and fourth quadrants; VSC is a circular area	Smaller than the PH topology	The same as the PH topology

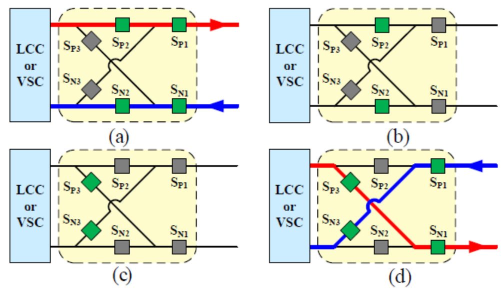

Fig. 11. Operation principle of reversal switch.

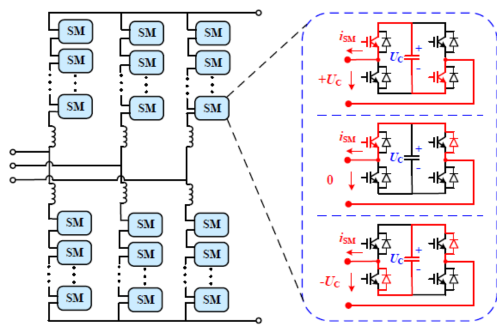

Fig. 12. Structure of FB-MMC.

Table 2
Comparison of power flow reversal.

Power flow reversal method	PH topology	TH topology	SCH topology	PCH topology
Installing reversal switch	Need LCC shutdown, earth current presents	Need system shutdown	Need system shutdown	Need LCC shutdown, no earth current
Adopting FB-MMC	Need LCC shutdown	No shutdown	Need system shutdown	No shutdown

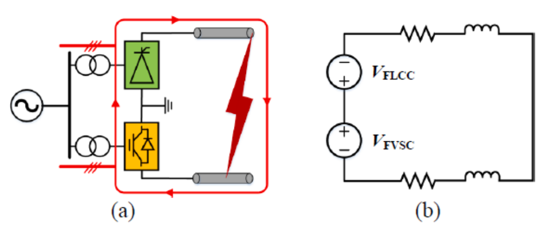

Fig. 13. Pole-to-pole fault on PH topology. (a) Fault current path. (b) Equivalent circuit.

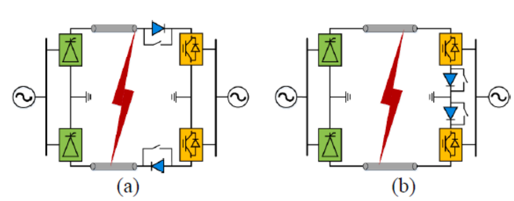

Fig. 14. Terminal-hybrid HVDC system with diodes. (a) Diodes on DC lines. (b) Diodes on the low-voltage side.

Table 3
Comparison of DC fault ride-through strategy.

	PH topology	TH topology	SCH topology	PCH topology
DC fault ride-through strategy	PTP fault can be cleared with LCC force retardation; extra device or control action is required to clear VSC PTG fault	Install diodes on the DC lines or on the low-voltage side of the VSC	Both PTP and PTG faults can be cleared with LCC force retardation	Trip ACCB, use DCCB or adopt fault-blocking converter is required

Table 4
Overall comparison.

Items	PH topology	TH topology	SCH topology	PCH topology
PQ operating zone	★★★★	★★	★★★	★★★★
Power flow reversal	★★★	★★★	★★	★★★★
DC fault ride-through	★★★	★★★	★★★★	★★

Note: more '★' indicates better performance in that field.