Fault response comparison of LCC–MMC hybrid topologies and conventional HVDC topology

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Abstract: The modular multilevel converter (MMC) can be used to upgrade conventional line commutated converter-based HVDC systems (LCC-HVDC), construct the hybrid topologies of LCC and MMC to acquire better fault responses. In this study, the mechanisms of three kinds of hybrid topologies for dc fault clearance are firstly analysed. Then the fault responses of the three hybrid topologies and the conventional LCC-HVDC topology are detailedly compared, including dc line fault and ac faults at both rectifier side and inverter side. The comparison helps demonstrate the degree of improvement when MMC is adopted to upgrade the conventional LCC-HVDC.

1 Introduction

In China, due to the uneven distribution of energy resources and load centres, long-distance bulk-capacity HVDC systems have been widely adopted in the west-to-east power transmission project. Generally, HVDC system of this kind has three common features [1]:

i. The power flow is usually unidirectional, namely from areas having rich energy resources to electricity-scarce areas.
ii. The power transmission capacity is large, meaning that the HVDC system is of high voltage rating and high current rating.
iii. Due to the long transmission distance (1000–3000 km), overhead line is adopted and the potential dc fault must be properly handled.

The line commutated converter-based HVDC (LCC-HVDC) system is a mature and widely adopted scheme for this scenario. However, the LCC-HVDC still has shortcomings. It consumes plenty of reactive power and produces significant harmonics, hence large area is needed for reactive power compensation and harmonic suppression [2]. Besides, commutation failure may occur during ac faults, leading to severe power loss and instability of ac system [3].

In recent years, the modular multilevel converter-based HVDC (MMC-HVDC) system, which has several advantages like no demand for harmonic suppression and reactive compensation, operation with passive or weak ac systems, and flexible control [4–6], shows attractive prospect in long-distance bulk-capacity power transmission. To deal with dc fault in the overhead line scenario, three approaches can be adopted for the MMC-HVDC: (i) tripping ac circuit breaker; (ii) tripping dc circuit breaker; (iii) adopting converters with dc fault ride-through ability. The first approach is the most economical and has been widely adopted in the cable scenario, but its fault clearance is relatively slow [7]. The second approach is the most straightforward, but its application to bulk-capacity power transmission is still lack of practical experience [8]. The third approach includes full-bridge submodule (FBSM) [9], clamp double submodule (CDSM) [10] and so on. Compared to the widely adopted half-bridge submodule (HBSM), the main shortcomings of this approach are the operation loss and the manufacturing cost. These shortcomings also exist for the dc circuit breaker approach.

To take fully use of the existing LCC-HVDC projects and the advantage of MMC-HVDC, several LCC–MMC hybrid topologies has been proposed [1, 11]. These topologies are able to deal with dc fault with the cooperation of LCC and MMC. Besides, the MMC in these topologies adopts HBSM, which means lower operation loss and manufacture cost compared to the FBSM and the CDSM.

In this paper, the structure of the potential LCC–MMC hybrid HVDC topologies are discussed, which helps explain the reason why the series connection of LCC and MMC still maintain the dc fault clearance ability. The ac and dc fault responses of these topologies are further compared, so as to demonstrate the contribution of MMC on the improvement of fault responses.

This paper proceeds as follows. Section 2 discusses three kinds of LCC–MMC hybrid topologies. The fault responses of these hybrid topologies as well as the conventional LCC–HVDC topology are detailedly compared in Section 3. In Section 4, the fault responses and some technical indexes are compared statically. A brief conclusion is made in Section 4.

2 Potential LCC–MMC hybrid topologies

As an attractive upgrade routine for conventional LCC-HVDC project, MMC can be adopted to replace part of LCC converters, constructing the hybrid topologies of LCC and MMC to acquire better fault responses. As shown in Fig. 1, the potential topologies include:

Type A: Hybrid topology adopting LCC at rectifier and series connection of diode and MMC at inverter;
Type B: Hybrid topology adopting series connection of LCC and MMC at both rectifier and inverter;
Type C: Hybrid topology adopting series connection of LCC and MMC at rectifier and series connection of diode and MMC at inverter.

The Type-A and Type-B topologies have been formally proposed [1, 11]. The Type-C topology is the further combination of Type A and Type B, which adopts the rectifier of Type B and the inverter of Type A, so that more LCC converters can be replaced by MMC.

For the above-mentioned hybrid topologies, the dc fault clearance ability is of the most concern if applied in the overhead line scenario. The mechanism of clearing dc fault for rectifier and inverter is explained below.
2.1 dc fault clearance for rectifier

In the Type-B and Type-C topologies, the rectifiers consist of LCC and MMC in series connection, in this configuration the dc fault current can be cleared by the force retard of LCC and the blocking of MMC.

As MMC in the aforementioned topologies adopt HBSM, under blocking state the flow path of dc fault current still exists for MMC. In this condition, the output voltage of LCC under force retard must be enough negative, which means that the dc voltage ratio of LCC and MMC must be objectively designed. In [1], the dc voltage ratio is deduced as

$$k = \frac{U_{LCC}}{U_{MMC}} > \frac{\sqrt{2}\cos 15^\circ}{2 \cos 15^\circ}$$  \hspace{1cm} (1)

Where $U_{LCC}$ and $U_{MMC}$ are the rated dc voltages of LCC and MMC, $\alpha_{FR}$ is the firing angle of LCC under force retard. It is easy to get that $k > 0.966$ when $\alpha_{FR} = 135^\circ$ and $k > 0.789$ when $\alpha_{FR} = 150^\circ$. This means that the clearance of dc fault current at rectifier side can be guaranteed if $U_{LCC}$ and $U_{MMC}$ are chosen equal, i.e., $k = 1$. The corresponding control strategy will be discussed in Section 3.

2.2 dc fault clearance for inverter

As the three kinds of hybrid topologies are used in the bulk-capacity long-distance scenario, the bidirectional power transmission is not required. In the inverter of these topologies, the diode (Type-A and Type C) or thyristor (Type B) is unidirectional for dc current, making the inverter fault current be naturally cleared if dc fault occurs.

Under dc fault condition, the LCC firing angle of Type-B topology should be forcedly settled to slightly $\geq 90^\circ$. The MMC in the inverter of all the three topologies should be blocked, or shifted to STATCOM mode to offer reactive power support for ac system.

3 Fault responses comparison

In this section, the fault responses of the aforementioned hybrid topologies as well as the LCC-HVDC topology will be compared, which helps demonstrate the superiority of the hybrid topologies over the conventional LCC-HVDC topology. The system parameters are listed in Table 1. The chosen rated voltage and rated capacity are in accordance with the scenario of long-distance bulk-capacity transmission. Note that, in the Type-B and Type-C topologies, the series-connected LCC and MMC bear half of the rated dc voltage, respectively. The control strategies for different types of converters are listed in Table 2. Also note that a backup constant dc current control is equipped at the rectifier MMC for the Type-B and Type-C topologies. This backup control, as proposed in [1], tries to raise the MMC output voltage during ac fault of rectifier side, so that the dc current can be better maintained. Other control strategies are widely known hence their details will not be explained for simplicity.

3.1 Ac fault at rectifier side

In this section, a near-end fault on three phases with line voltage dropping to 30% is applied at the rectifier side for the four topologies. The fault is applied at 1.5 s and lasts for 0.1 s, the simulation results of the four topologies are compared in Fig. 2. Note that the ac voltage responses for the four topologies are quite similar, hence only the ac voltage in the Type-A topology is demonstrated.

Generally, the active power is of the most concern under ac short-circuit fault, for the power loss reflects the severity of the shock on the ac system. As shown in Fig. 2d, the active power is maintained and restored the best in the Type-B topology, for the reason that the dc current of the Type-B topology can be largely maintained (see Fig. 2c).

The response differences under rectifier side ac fault can be further explained by the physical difference of LCC and MMC. The LCC belongs to current source converter, the output voltage of which largely depends on the ac system and can be quickly adjusted if the ac voltage is normal. The MMC, on the other hand, belongs to voltage source converter, its output voltage comes from the internal capacitor and its rate of regulation is relatively slow. In the condition of severe ac fault, the output voltage of rectifier LCC is largely reduced. If the inverter cannot quickly reduces its output dc voltage, current cut-off will occur and lead to severe power loss, which is in accordance with the observed responses in the Type-A and Type-C topologies. As for the LCC-HVDC topology, even though the inverter has the backup constant dc current control, the dc current is still restricted due to the voltage dependent current order limiter (VDCOL) control.
It should also be noted that the MMC in the rectifier acts as ‘footstone’ for dc voltage, which contributes to the recovery of dc current. As can be noticed in Fig. 2c, the Type-B and Type-C topologies, which partly adopt MMC in the rectifier, appear faster recovery rate than other topologies that wholly adopt LCC as rectifier.

3.2 ac fault at inverter side

In this section, a near-end fault on three phases with line voltage dropping to 30% is applied at the inverter side for the four topologies. The fault is applied at 1.5 s and lasts for 0.1 s, the simulation results of the four topologies are compared in Fig. 3. Similar to Section 3.1, only the ac voltage in the Type-A topology is demonstrated, for the ac voltage responses for the four topologies are similar.

The resistance ability to inverter side ac fault can also be evaluated by the response of active power. Fig. 3d shows that all the three hybrid topologies response better than the conventional LCC-HVDC topology. This is because the inverters of the three topologies partly or wholly adopt MMC, which do not have the commutation failure problem and are able to maintain power transmission ability. Among the three hybrid topologies, the performance of Type-B topology is slightly inferior, for commutation failure exists for the inverter LCC.

An interesting phenomenon can be found by analysing the dc voltages and dc currents. During the fault period, the topologies with inverter of series-connected diode and MMC express increasing dc voltage and decreasing dc current, contrary to the usual response of decreasing dc voltage and increasing dc current. This is because the decrease of ac voltage restricts the output active power; the surplus energy will be stored in the capacitors of MMC, leading to the increase of inverter dc voltage. As the dc current regulation ability at rectifier side is limited, the increase of inverter dc voltage will lead to the drop of dc current. In this sense, arrester is needed at the dc side of inverter so as to restrict dc overvoltage.

3.3 dc fault

Though the four topologies have different structure, their dc fault clearance strategy can be illustrated using one flow chart, as shown in Fig. 4.

The kernel of the dc fault clearance strategy is the force retard of LCC and the blocking (or shifted to STATCOM mode) of MMC. During the dc fault period, the rectifier MMC must be blocked and the rectifier LCC should be forcedly shifted to inverter mode. Note that the firing angle is set according to the real-time dc current. The control of the inverter is relatively simple; hence the detailed explanation will not be given.

The clearance of dc fault by the four topologies is compared in Fig. 5. It can be found that the capability of clearing dc fault of the four topologies is close, with 90% power recovery time of ∼0.5–0.7 s after fault occurs. The main difference is the duration of clearing rectifier dc fault current. This is because MMC under blocking condition still outputs positive dc voltage, the time for the Type-B and Type-C topologies to fully clear the dc fault current is longer.

4 Technical comparison

In this section, the performance of the hybrid topologies and the conventional LCC-HVDC topology during fault period will be compared more directly based on the simulation results above. Other characteristics, including operation loss and filter
requirement, will also be compared. Table 3 shows the comparison results. Note that the recovery time is calculated from the time the fault is cleared for ac faults and from the time the fault occurs for dc faults.

For the conventional topology, the full load operation loss excluding the loss in transmission line is \( \sim 0.75\% \), and for the MMC-based HVDC it is \( \sim 1\% \) [12, 13]. Based on that, the operation loss for the three hybrid topologies is calculated as listed in Table 3, which means that the loss of the hybrid topologies is slightly larger than that of the conventional topology. It is also shown in Table 3 that the hybrid topologies contribute to reducing the reactive power requirement. Note that in the calculation the MMC is not considered for offering reactive power support for LCC. If considered, the reactive power requirement can be further reduced.

### 5 Conclusion

In this paper, the fault responses of three potential LCC–MMC hybrid HVDC topologies as well as the conventional LCC-HVDC topology are compared. The comparison shows that these hybrid topologies are of better performance than the LCC-HVDC topology under ac faults at both rectifier side and inverter side. Besides, the dc fault clearance ability of these hybrid topologies are close to the LCC-HVDC topology. Considering the economy efficiency and fault performance, these hybrid topologies can be used to update the existing LCC-HVDC project in the scenario of long-distance bulk-capacity power transmission.

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**Fig. 3** Response comparison of ac fault at inverter side
(a) ac voltage in Type-A topology, (b) dc voltage, (c) dc current, (d) Active power, (e) Reactive power, (f) Extinction angle

**Fig. 4** DC fault clearance strategy

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Table 3 Technical comparison

|                        | Type-A          | Type-B          | Type-C          | LCC-HVDC        |
|------------------------|-----------------|-----------------|-----------------|-----------------|
| Control reactive power | inverter        | rectifier and inverter | rectifier and inverter | No              |
| Operation loss         | 0.875%          | 0.875%          | 0.9375%         | 0.75%           |
| Reactive power compensation requirement | 40–60% (rectifier) | 20–30% | 20–30% (rectifier) | 40–60%          |
| Recovery time of rectifier ac fault, ms | 400 | 200 | 400 | 400 |
| Recovery time of inverter ac fault, ms | 150 | 100 | 100 | 200 |
| Recovery time of dc fault, ms | 600 | 500 | 700 | 500 |

Fig. 5 Response comparison of dc fault
(a) Type-A topology, (b) Type-B topology, (c) Type-C topology, (d) LCC-HVDC topology
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