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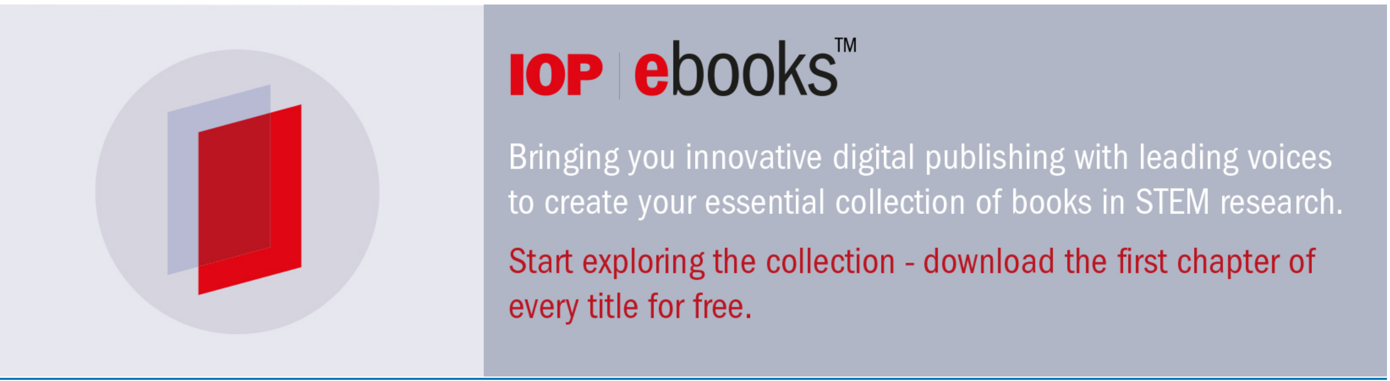

Active Power Shifting Strategy for the Bipolar VSC-MTDC

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Abstract. Currently, the bipolar VSC-MTDC has become increasingly popular in practical projects. With the traditional wiring mode, line overload, generator tripping or load shedding may occur if a DC line or converter quits operation. While with a more flexible bipolar wiring mode, power shifting from the faulty network to the healthy one is permitted under same conditions. This paper proposes an active power shifting strategy based on bipolar VSC-MTDC. Since the positive-pole and negative-pole networks can be controlled independently, the transmitted power of the healthy pole network can be increased and that of the faulty pole network can be decreased, which is to avoid power surplus under abnormal operation conditions. This strategy has improved the reliability and transmission capacity of VSC-MTDC system. Then a 4-terminal MTDC simulation is established in PSCAD/EMTDC. The validity of the proposed strategy has been proved by the simulation results.

1. Introduction

High-voltage direct current transmission based on voltage source converter (VSC-HVDC) is a competitive technology in the smart grid. Using fully controlled device IGBT and pulse width modulation (PWM) technology, VSC-HVDC shows advantages over line-commutated converters (LCC-HVDC). For example, VSC-HVDC technology provides an independent control of active power and reactive power, as well as the ability to constitute multi-terminal HVDC (MTDC) system. The flexible power control in MTDC results in a more complex cooperation in the control targets [1].

Recently, different cooperative control strategies for VSC-MTDC have been studied. These strategies can be categorized into master-slave control and DC voltage droop control [2, 3]. Most of the existing researches focus on the control strategies for traditional VSC-MTDC where a single set of converters is shared by the positive and negative poles. While with a demand for a higher voltage level and larger power transfer capability, the bipolar VSC-MTDC has been paid attention to and applied to practice gradually, such as the Xiamen ±320kV MTDC project [4]. In the bipolar VSC-MTDC, each converter station consists of two individual converters for different poles. The positive-pole network and negative-pole network can operate independently. The feature enables the active power to be shifted actively from the faulty pole to the healthy pole under fault conditions.

Hence this paper considers an active power shifting strategy for the bipolar VSC-MTDC. The bipolar system adopting the power shifting strategy will possess the following merits: 1) The maximum available power (MAP) [5] is the maximum power that can be transmitted in the HVDC link. The active power transmission of the faulty pole can be decreased so that the power of this pole can be controlled within MAP; 2) The faulty pole still transmit a part active power rather than quit operation entirely by reasonable power distribution, which enhances the integral power transmission capacity of the bipolar system under fault conditions.

Therefore, the research on active power shifting strategy under abnormal operation conditions possesses theoretical value and engineering practical value.

2. The topology and features of the bipolar VSC-HVDC

2.1. The topology of the bipolar VSC-HVDC

Figure 1(a) shows the topology of a terminal of the bipolar system, where an AC grid connected to a terminal of the bipolar VSC-HVDC system. In the bipolar VSC-HVDC, the positive-pole subsystem and the negative-pole subsystems are structurally symmetrical, and fully decoupled on the DC side. Each converter station consists of two individual converters, one is for the positive-pole network (VSC^{+}) and the other is for the negative-pole network (VSC^{-}). Their joint point between these two subsystems on the DC-side is designated as the ground point. A metallic wire is set up as the neutral line to provide a return circuit, so that the positive-pole network and negative-pole network can operate independently via the neutral line. While on the AC side, the two individual converters are connected to the PCC AC bus via two parallel-connected transformers, respectively.

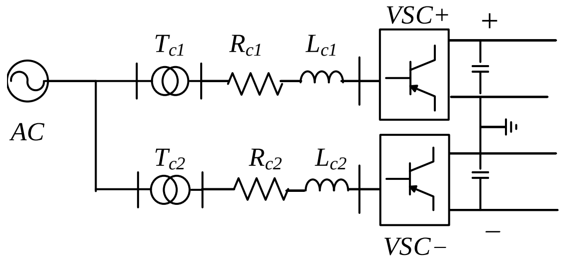

Figure 1. Block diagram for bipolar VSC-HVDC connected to AC system

2.2. The characteristics of the bipolar VSC-HVDC

Compared with the traditional VSC-HVDC, the bipolar VSC-HVDC as shown in Figure 1enables an independent control for the positive and negative poles and it has the following features:

1) Independent operation of the positive-pole and negative-pole networks: This structure makes the system possible to operate under symmetrical bipolar operating mode or asymmetrical mode where the current through the positive pole network is not equal to the current through the negative pole network. Furthermore, as the system can operate under asymmetrical mode, the positive pole and negative pole networks have the possibility to be controlled separately, and to be applied the active power shifting strategy to.

2) Higher power supply reliability. The bipolar VSC-MTDC has two independent converters at its DC terminal for the positive-pole and negative-pole networks, respectively. When a fault or a regular maintenance takes place on the DC side of a single pole, only the abnormal pole is affected, while the other pole can still operate normally. The above feature will enhance the HVDC system reliability.

3. The control principle of the active power shifting strategy

3.1 The basic control principle of the active power shifting strategy

Virtually the proposed active power shifting strategy is a coordinating control of the positive-pole network and negative-pole network under an asymmetric operation mode. When a failure or maintenance takes place on the DC side of a single pole, to ensure the transmission capacity of the MTDC system, the strategy is used to increase the transmission power of the healthy pole and to decrease the transmission power of the abnormal pole.

Coordinating ability of the two poles can enhance the reliability of the grid. Under abnormal operation conditions, the failure information of converters and DC lines are provided as criteria to implement the corresponding active power shifting strategy. The proposed strategy follows the following control principle:

Step1: Obtain the steady-state information. The upper control system keeps recording the original active power and voltages at each terminal from the steady-state operation moment.

Step2: Recognize the abnormal condition. After a failure or maintenance, the control system is to judge the fault type, recognize the DC networks topology and mark the detective converter of DC line.

Step3: calculate the system flow. According to the topology and the original power as well as voltage at each terminal, the transmitted power and currents through the converters can be calculated. The transmitted power and currents in the DC lines can also be obtained by load flow calculation.

Step4: Verify the constraints. The constraints should be verified to secure the operation of the system, which includes the transfer capacity of converters, the maximum transmitted power and currents of the DC lines. If the constraints are satisfied, the active power shifting process is completed. In contrast, if the constraints are not satisfied, step 5 is needed to modify the active power reference of the relevant converters.

Step 5: Modify the active power reference. Since the constraints are not satisfied, the control reference of the converter connected to the abnormal DC lines should be modified. The adjustment principle will be introduced in detail in Section 3.2.

3.2 The adjustment principle of the active power reference

In the proposed strategy, the control reference of the two poles at a terminal should be adjusted synchronously to maintain the total transmitted power constant through this terminal. Assume that: under normal operation conditions, P_{ref0} is the original active power reference for the converter of a single pole; under abnormal operation conditions, P_{ref_h} is the active power reference for the converter of the healthy pole after adjustment; P_{ref_f} is the active power reference for the converter of the faulty pole after adjustment, ΔP_{ref} is the power reference variation.

Under the following two abnormal conditions, the adjustment principle of active power shifting strategy should obey formula (1) : *a.* a converter of a single pole quits operation *b.* a DC line quits operation and the VSC connected to it has only one outgoing DC line (this faulty DC line).

$$\begin{cases} P_{ref\_h} = \min\left\{P_{VSC\_\max}, 2P_{ref0}\right\} \\ P_{ref\_f} = 0 \end{cases} \tag{1}$$

Where $P_{VSC\_\max}$ is the maximum transmitted power of the VSC whose active power reference needs to be adjusted.

Under these operation conditions, the healthy pole should ensure the transmitted power through the DC networks to avoid generator trip or load shedding. Hence the active power reference of the healthy-pole VSC should be increased and that of the faulty –pole VSC should be decreased. If the initial overall transmitted power at this terminal exceeds the capacity of single VSC, the power reference of the healthy-pole VSC is set to $P_{VSC\_\max}$. Otherwise, the power reference is set to overall transmitted power of the two poles under the normal condition. Because the VSC of the faulty pole lose the transmission ability, its power reference is set to 0.

2) If a DC line quits operation and the VSC connected to it has more than one outgoing DC lines, the adjustment principle of active power shifting strategy should obey formula (2):

$$\begin{cases} \Delta P_{ref} = P_{dc\_fault} - \sum_{k=1}^{m} \Delta P_{dck} \\ P_{ref\_h} = P_{ref0} + \Delta P_{ref} \\ P_{ref\_f} = P_{ref0} - \Delta P_{ref} \end{cases} \tag{2}$$

Where P_{dc_fault} is the transmitted active power in the faulty DC line before the failure; the VSC connected to it has m outgoing DC lines which do not reach MAP, $\sum_{k=1}^{m}\Delta P_{dck}$ is the sum of the active power margin in the DC lines.

4. Simulation

In order to verify the validity of the proposed active power shifting strategy, a bipolar 4-terminal VSC-MTDC simulation system was built in PSCAD/EMTDC. The topology of the system is shown in Figure 2. Each terminal has two individual converters, which are connected to positive-pole network and negative-pole network, respectively. Terminal 1 and terminal 3 are rectifier stations. Terminal 4 is an inverter station. Terminal 2 is a balanced station which operates under DC voltage control. The rated DC voltage is ±500kV. The upper and lower limits of active power as well as the control strategy for each converter are demonstrated in Table 1.

Table 1. The limits of active power and control strategy for each converter station

Terminal	Control strategy	$P_{dc\,max}$ (MW)	$P_{dc\,min}$ (MW)
T1	Active/reactive power decoupled control	2×750	0
T2	DC voltage control+ Reactive power control	2×1500	-2×1500
T3	Active/reactive power decoupled control	2×750	0
T4	Active/reactive power decoupled control	0	-2×750

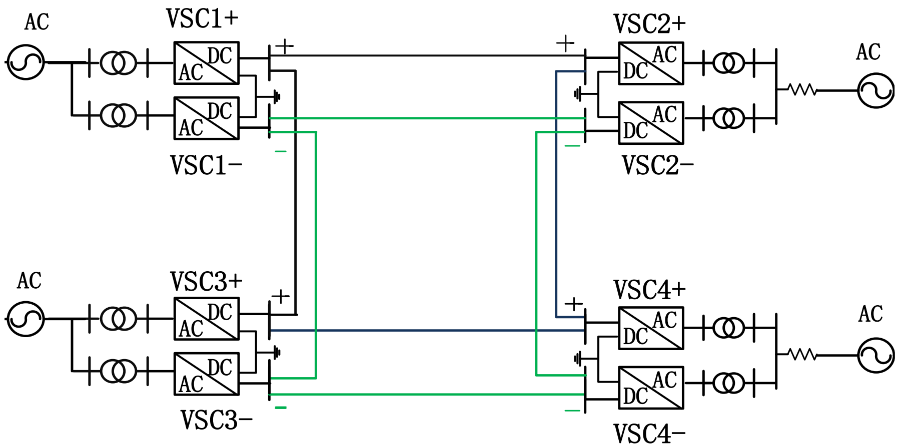

Figure 2. The topology of a 4-terminal VSC-MTDC

4.1. Case 1: Control performance during DC line disconnection failure

In the set case, the active power reference of VSC1+ and VSC1- are 600MW; the active power reference of VSC3+ and VSC3- are 1200MW; the active power reference of VSC4+ and VSC4- are -1000MW. The converters of terminal 2 operate under DC voltage control and reactive power control (the reactive power reference is 0 MVar).

The system reaches steady state at 5.0 s. The maximum transmitted active power of the system is the active power in the DC line between terminal 3 and terminal 4. Hence a disconnection failure is set in this positive-pole DC line to observe the system performance.

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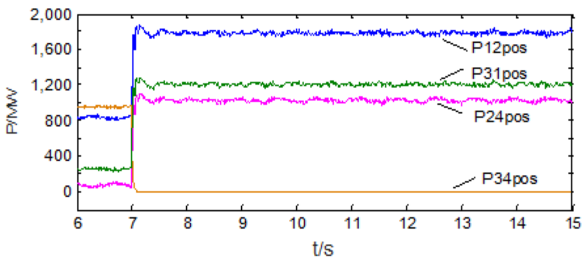
Figure 3 (a)(c)(e) presents the system performance without using the active power shifting strategy, and Figure 3(b)(d)(f) presents the system performance using the active power shifting strategy. P_{12pos} P_{24pos} P_{31pos} P_{34pos} refer to the transmitted active power in the positive-pole DC lines. P_{12neg} P_{24neg} P_{31neg} P_{34neg} refer to the transmitted active power in the negative-pole DC lines. U_{dc_pos} and U_{dc_neg} are the positive-pole and negative-pole DC voltages, respectively.

Considering the equipment manufacture standard, the maximum current capacity of direct current breaker for ±500kV network is 3kA and the MAP is 1500MW. 1.05 times long-term over-current (3.15kA) is acceptable.

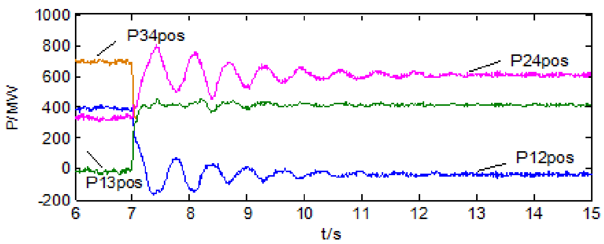
As presented in Figure 3(a), the transmitted active power reaches 1800MW and the DC current reaches 3.6kA, which seriously affects the network's stable and secure operation. Under this circumstance, the positive-pole DC line disconnection failure does not influence the operation of the negative-pole network. However, the overall transfer capacity of the bipolar VSC-MTDC is decreased.

Therefore, the implementation of the active power shifting strategy is a preferable option. According to the control flow in Section 3, the active power reference of VSC1+ and VSC3+ should be decreased in a proper sequence. At the same time, the active power reference of VSC1- and VSC3- should be increased. The active power reference of VSC1+ and VSC1- are adjusted to 450MW and 750 MW. And the active power reference of VSC3+ and VSC3- are adjusted to 900 MW and 1500MW, respectively. Because of the appropriate change of control references, the DC voltages undergo a fluctuation within 1 second after the failure and return to original value 3 seconds later. Using the active power shifting strategy, the transmitted active power can be controlled within the maximum current capacity of the direct current breaker. During DC line disconnection failure, the proposed strategy is an effective solution to the line over-load problem.

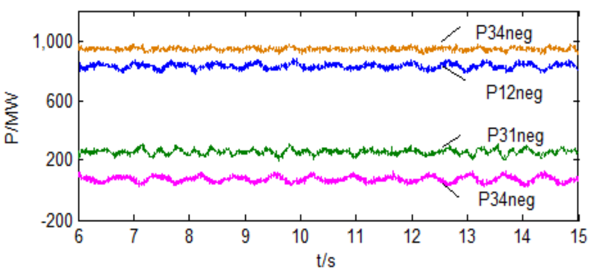
(a) the positive-pole transmitted active power(using the strategy) (b) the positive-pole transmitted active power(without using the strategy) (c) the negative-pole transmitted active power(using the strategy) (d) the negative-pole transmitted active power(without using the strategy) (e) the positive-pole DC voltage (using the strategy) (f) the negative-pole DC voltage (without using the strategy)



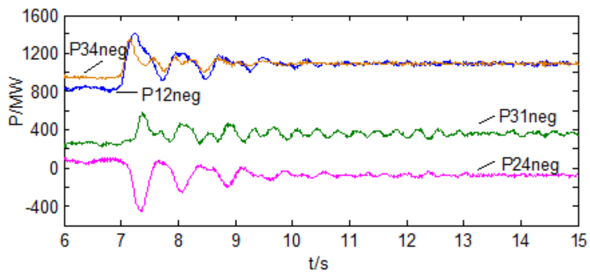
(a)



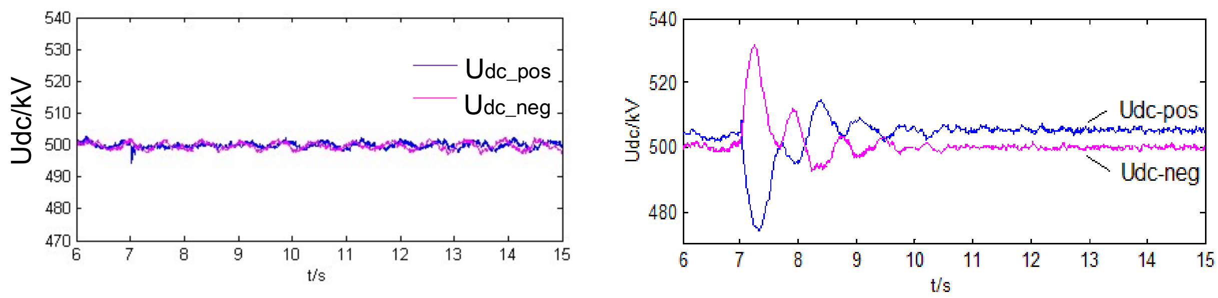
(b)



(c)



(d)



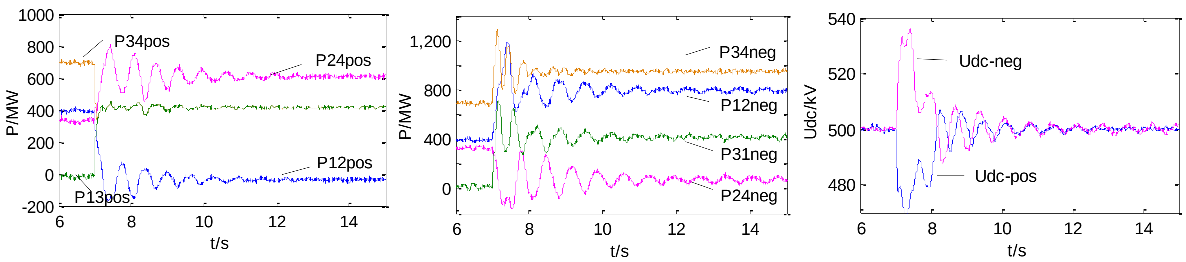
(e) (f)

Figure 3. system performance during DC line disconnection failure

4.2.Case 2: Control performance during converter blocking failure

This case is simulated to observe the system performance during a unipolar VSC blocking failure. Under normal conditions, the converters' active power reference of terminal 1, terminal 3 and terminal 4 are 400MW, 700MW and -1000MW, respectively. DC voltage control for terminal 2 stabilizes the DC voltages of the networks.

The positive-pole converter of terminal 3 quits operation at 7.0 s. The AC bus of terminal 3 can still operate normally during the converter blocking failure, so that the positive-pole DC network is changed from a 4-terminal MTDC to a 3-terminal MTDC.



(a) (b) (c)

Figure 4. System performance during converter blocking failure (using active power shifting strategy) (a) the positive-pole transmitted active power (b) the negative-pole transmitted active power (c)the DC voltages of the bipolar networks

In ideal conditions, the generator trip failure does not occur to the generators in the AC system. Thus the power supply to terminal 3 retains 1400 MW which is within the transfer capacity of the connected negative-pole VSC. Figure 4 shows the curves of transmitted active power and DC voltages. The negative-pole network's input active power exceeds its output power so that the negative-pole DC voltage rises to 530 kV within 3 seconds after the failure. By contrast, the positive-- pole network's input active power is inferior to its output power so that the DC voltage reduces to 470 kV.

If the active power shifting strategy is not adopted after converter blocking failure, each converter's active power reference remains the same as it begins. The overall transmitted power from terminal 3 have to be declined to the half of the original generated power and a part of generators need to quit operation, which may attribute to dynamic instability of the isolated wind farms. Therefore, the active power shifting strategy helps avoid the generator tripping of the wind farms.

5. Conclusion

This paper has proposed a novel active power shifting strategy which controls the active power distribution between bipolar networks under abnormal conditions. According to simulation results, the effectiveness of the proposed control strategy has been proved:

1) Taking advantages of bipolar networks' cooperation, the transmitted power of faulty pole network will decline to below MAP.

2) The proposed strategy effectively reduces the risk of generator or load shedding. Hence the generated power can be sent out as much as possible and frequency fluctuation will be lower.

3) Due to the independent control of the positive and negative networks, the transmitted active power's value and direction of corresponding DC lines can be different. The proposed control strategy has good feasibility in the bipolar VSC-MTDC.

Acknowledgement

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