Simulation study on commutation failure control and recovery of UHVDC with hierarchical connection mode

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Abstract. UHVDC transmission projects with hierarchical receivers are connected in series on the DC side. When a single voltage level of AC system fails, commutation failure may occur in both hierarchies of DC system, and the impact will be more serious when the electrical connection is strong. In the process of fault recovery, inappropriate control strategy will also lead to successive commutation failures. In this paper, a commutation failure control and recovery strategy based on real-time fault detection and determination is proposed. In view of the instantaneous faults of AC system, the starting time is determined according to the predicted results of commutation failure, so as to reduce the starting times and prevent the continuous commutation failure in the recovery process. When the single-hierarchy AC system is permanently severely faulted, the fault hierarchy is isolated and the non-fault layer operates normally. The PSCAD/EMTDC simulation model of an UHVDC transmission project is built. Instantaneous and permanent faults are set up to simulate. It is verified that the proposed strategy can effectively reduce the number of successive commutation failures and improve transmission reliability.

1. Introduction

With the development and wide application of HVDC technology, the DC voltage level and capacity of transmission have been continuously improved. In order to improve the power flow evacuation and voltage supporting ability in the receiving end system, UHVDC (ultra-high voltage direct current) project with hierarchical access to AC system at the receiving end has gradually developed [1]. Because of the unique series structure of UHVDC’s dual 12-pulse converter, the failure of a single voltage level in the receiving power grid will lead to the commutation failure of the 12-pulse converter connected to it [2]. In the recovery process of UHVDC after fault elimination, two groups of 12-pulse converters may fail to commutate for many times simultaneously when the current produced by control system regulation changes greatly. It may impact the DC system and even cause it to shut down [3]. If the AC system with different voltage levels at the receiving end is close to each other, the effect of commutation failure is more serious. Therefore, how to reduce the number of commutation failures and the impact on the other 12 pulsation converters in the recovery process after commutation failure of one 12-level pulsation converter is an urgent problem to be solved for the UHVDC with hierarchical receivers.

At present, most of the researches focus on commutation failure of single-hierarchy DC system and multi-feed DC system [4, 5]. But the researches on the receiving-end hierarchical DC system is
not enough. Most studies only focus on the suppression of one commutation failure [6, 7], while few studies focuses on multiple commutation failures during failure and its recovery process [8-10].

When the current of DC line increases sharply due to the fault of receiving power grid, commutation failure of 12-pulse converter occurs. Automatic restart control is often used in DC projects to rapidly reduce DC fault current and gradually return to the normal operation of the DC system. After the control reaches the preset restart times, the outage signal is sent to stop the operation of the DC system. However, this control usually uses fixed time interval restart [11, 12], which may lead to successive commutation failures in the process of fault recovery and impact the AC/DC system.

In this paper, a hierarchical UHVDC project is taken as an example to improve the conventional automatic restart control, and a commutation failure control and recovery strategy based on real-time fault detection and determination is proposed. The PSCAD/EMTDC simulation model of the UHVDC project is built, and the transient faults of two-hierarchy voltage levels and permanent faults of single-hierarchy voltage levels are simulated and analyzed. The results show that the proposed strategy can effectively reduce the number of successive commutation failures and improve the reliability of transmission.

2. Introduction of receiver system

The high-end and low-end valve groups of the receiving converter station of an UHVDC project are connected to 500 kV and 1000 kV AC systems of a provincial power grid respectively. Half of its capacity is absorbed in the province where the receiving station is located, and the remaining half is transferred to the surrounding provinces. This method is helpful to balance the power flow, guide the power flow, and make the large capacity DC power dispersed and absorbed reasonably.

The AC and DC sides of 12-pulse converter units (including valve group C and converter T) should not be high voltage (or low voltage) in both side, so as to balance the insulation coordination level of windings on both sides of converter and reduce the manufacturing difficulty and cost. Therefore, as shown in Figure 1, the high-end valve group \( C_H \) and the low-end valve group \( C_L \) are connected to the power grid with rated voltage grades of 500 kV and 1000 kV respectively. The subscripts 1 and 2 of each variable in the graph indicate the positive and negative poles respectively. AC filter ACF and reactive power compensation device \( Q_c \) are also connected in parallel on 500 kV and 1000 kV converter buses respectively. \( C_H \) and \( C_L \) are equipped with high-speed bypass switches \( BPB \) to isolate a single 12-pulse converter unit from the DC system. But the number of valves in rectifier station and inverter station is always the same. Every pole DC line is equipped with flat-wave reactor \( L_d \) and DC filter. \( U_H \) and \( U_L \) are high and low converter bus voltages, respectively. It is necessary to configure an independent controller to achieve flexible control of a single 12-pulse converter unit.

![Figure 1. Schema of Receiver Hierarchical Access Architecture.](image)

![Figure 2. Equivalent circuit of electrical connection between different voltage levels of UHVDC receiver with hierarchical connection.](image)
As can be seen from Figure 2, when there is an electrical connection between the two levels of voltage, one level of AC system will fail and the other level of AC system will inevitably be affected. When there is no electrical connection or very weak connection between the two voltage levels at the receiving end, it can be equivalent to no $T_{HL}$ and $Z_{HL}$, that is, the switch S is disconnected.

### 3. Commutation failure and conventional automatic restart control

#### 3.1. Commutation failure

A semi-controlled power electronic device—thyristor, is used in this UHVDC project. Its interruption should take enough time: under the reverse voltage, a few carriers need to be migrated, diffused and recombined to re-establish the potential barrier and restore the forward voltage interrupting ability, which can be expressed by the intrinsic limit interruption angle $\alpha$. If the DC system is disturbed, the reverse pressure time of the converter valve on the inverting side is less than that. When the voltage added to the converter valve is positive, the converter valve will be re-opened and reversed to the rigid-opened converter valve. This process is called commutation failure.

Commutation failure can be divided into one commutation failure and successive multiple commutation failure. One commutation failure refers to the return to stable operation of a DC system after only one commutation failure, including one commutation failure in a single-hierarchy DC system and one commutation failure in two hierarchies simultaneously. Continuous multiple commutation failures refer to two or more commutation failures in single-hierarchy DC system and two or more commutation failures in another hierarchy’s DC system.

#### 3.2. Automatic restart control

When serious faults of AC system lead to successive commutation failures of converter valves, the existing control and protection system of DC project will start automatic restart control, which includes two sequential control instructions: fast phase shifting and restart.

- **Fast phase shifting:** the firing angle of the rectifier increases rapidly from the rated value of 15° to 120°–150° and becomes the operation of the inverter. The trigger angle of the inverters rapidly changes from about 135° to more than 160°. Therefore, the energy stored in the DC line is rapidly flows into the AC system at both ends, which causes the DC current to drop rapidly to zero within 20–40 ms.

- **Restart:** When DC current is zero, the firing angle of rectifier can be quickly restored to 15° after 100ms to 500 ms for arc de-dissociation. The rated DC voltage and current can be established according to normal start-up mode, i.e. full voltage restart. If the insulation at the fault point fails to recover in time and the first full voltage restart fails, the second restart may prolong the time of de-ionization or reduce the DC voltage. If the second restart fails, the third step-down (0.7pu) restart can also be carried out, such as the San-Chang DC project. When the preset restart times are reached (usually up to 4 times) but all fail, the outage signal is sent out to block the converter, which makes the DC system outage.

It can be seen that the existing automatic restart control depends on experience to set the start time and times. If the fault is not eliminated and restart, it will aggravate the degree of commutation failure and cause multiple impacts on AC and DC systems.

### 4. Commutation failure control and recovery strategy

When the AC system fails, the converter bus voltage changes accordingly. Based on this, the type, status and location of the fault are detected and judged, and corresponding operation signals are sent out. Real-time fault detection and judgment is shown in Figure 3. It consists of two parts: real-time fault detection and fast phase shift/restart judgment. This part is configured at each level of the receiving end.
4.1. Real-time fault detection

When the single-phase-to-ground fault occurs in the receiving AC system, the zero-sequence voltage component will appear in the converter bus voltage $u_0$:

$$u_0 = u_a + u_b + u_c$$  \hspace{1cm} (1)

$u_a$, $u_b$, and $u_c$ in (1) are the measured value of three-phase voltage of converter buses.

When the three-phase ground fault occurs in the receiving AC system, the voltage rotation vectors $u_\alpha$ and $u_\beta$ of the converter buses on axes $\alpha$ and $\beta$ are obtained by using the $abc-\alpha\beta$ coordinate transformation shown in (2).

$$\begin{align*}
  u_\alpha &= \frac{2}{3} u_a - \frac{1}{3} (u_b + u_c) \\
  u_\beta &= \frac{1}{\sqrt{3}} (u_b - u_c)
\end{align*}$$  \hspace{1cm} (2)

The rotation vector $u_{rot}$ is as in

$$u_{rot} = \sqrt{u_\alpha^2 + u_\beta^2}$$  \hspace{1cm} (3)

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**Figure 3. Schematic diagram of real-time fault detection and decision controller.**

As can be seen in Figure 3:

- When single-phase fault occurs in AC system, the zero-sequence component of converter bus voltage will increase rapidly. If the absolute value of $u_0$ is greater than the set value of $u_{0_{\text{ABS}}}$, the output angle of $\theta$ reflects the severity of fault and commutation failure.

- When three-phase faults occur in AC system, $u_{rot}$ will increase rapidly. If the difference between $u_{rot_{\text{diff}}}$ and the value before faults is larger than the set value, the output angle $\theta$ reflects the severity of faults and commutation failures.
In this fault detection link, \( \theta \) is limited to \([0^\circ, 25.8^\circ]\), as the input value of the fast phase shift/restart decision link.

4.2. Commutation failure control and recovery strategy

The process of commutation failure control and recovery strategy is shown in Figure 3 after the signal \( X_{Hi} \) (i = H, L) is sent out by the decision link. 'i' means high-end and low-end. Permanent serious faults occurring in two AC systems with different voltage levels are beyond the scope of this paper. Turn-off of high-power thyristors takes about 400 \( \mu \text{s} \), \( \gamma_{\text{min}} \) is 7.2\(^\circ\) (at 50Hz). Because the rated firing angle is 15\(^\circ\), when \( \theta \) is bigger than threshold (7.8\(^\circ\)), the fast phase shift/restart control is triggered.

4.2.1. Single-hierarchy fault control flow. Serious instantaneous faults occur in hierarchy i of AC system. \( X_{Hi} = 0 \) is output in the judgment link, which makes power instruction \( P_{\text{ref}} \) and DC voltage instruction \( U_{\text{dref}} \) to be 0. System control mode is changed into inverted instruction, which makes rapid phase shift and reduces fault stress (converter is not locked). DC power evacuates rapidly through rectifier and inverter stations. Meantime DC current drops to zero quickly. After detecting the removal of fault and finishing de-dissociation, \( X_{Hi} = 1 \) and \( X_{Li} = 1 \), making \( P_{\text{ref}} \) and \( U_{\text{dref}} \) to be 1.0pu. The rectifier side converter is converted back to the rectifier state, and the system restarts to realize automatic restart.

In this paper, it is assumed that a permanent fault is determined if the hierarchy i fault is not cleared after 1 s of fault occurring, and the hierarchy i of DC system needs to be shut down. The two-station’s hierarchy i converter unit closes the bypass switch. Firstly, close the hierarchy i rectifier unit. Then close the hierarchy i converter unit on the inverter side, so that the fault unit is isolated. After the control system is switched to bipolar half-voltage mode, the firing angle at the rectifier side, the turn-off angle at the inverter side and the DC current are still rated and \( P_{\text{ref}} \) and \( U_{\text{dref}} \) are changed to 0.5pu.

4.2.2. Coordination of interhierarchy recovery strategies. Serious faults of single-hierarchy voltage level occur when there is electrical connection between different voltage levels of AC system, or serious faults occur in double-hierarchy AC system without electrical connection between AC systems, both of which will cause commutation failure of two-hierarchy DC system. Therefore, coordination of recovery strategies between hierarchies should be taken into account.

\( X_{Hi} \) still holds to be 0 when the voltage of two-hierarchy converter buses is reduced at a transient fault. The flow chart according to Figure 4 can still run normally.

5. Simulation verification

According to the actual engineering parameters of UHVDC mentioned, a model is built in the electromagnetic transient simulation platform PSCAD/EMTDC. The proposed commutation failure control and recovery strategy based on real-time fault detection and determination is added to the actual control system.

In the following simulation results, "Recovery Strategy Control" means that commutation failure control and recovery strategy based on real-time fault detection and determination are used, while "Conventional Control" means that the recovery strategy mentioned in this paper is not adopted. In the figure, \( X_{Hi} \) is the control signal of the fast phase-shifting/restart decision output of the high-end and low-end AC/DC systems. \( I_d, U_d \) and \( P_d \) are positive DC current, voltage and power respectively.

5.1. Permanent failure of low-end AC system

Three-phase grounding fault occurred when the low-end 1050 kV converter bus of inverter station was set for 3 s. There was no electrical connection between the two hierarchies, and the lowest value was 0, keeping 1.0 pu. The control strategy and DC system response under permanent faults of single-hierarchy AC system are shown in Figure 4.
According to XH, because the fault always exists, regulation fails at time B under the conventional control. Then the system is in abnormal operation. Under the control of recovery strategy, after time A, $X_{HL} = 0$, fast phase shifting. After 1s, the fault still exists. The fault unit is isolated and locked at time C, and then restarted by bipolar half-voltage operation mode.

Under the conventional control, $I_d$ increases sharply, up to 2.5pu, and then stabilizes to 0.3pu under the action of low voltage current limiting. At time E, $P_d$ was stable at 0.17pu. Under the control of recovery strategy, the maximum is only 1.25pu, and then it is reduced to 0 immediately. Under the action of low voltage current limiting, $U_d$ starts at 0.5pu, $I_d$ starts at time D, and reaches the steady value of 1.0pu at time F, and $P_d$ stabilizes at 0.5pu.

It can be seen that the proposed control strategy can not only reduce the risk of commutation failure under permanent faults, but also make the DC system in the non-fault hierarchy continue to operate normally, conveying 50% power, and only the DC system in the fault hierarchy is out of operation.

### 5.2. Instantaneous faults in low-end AC systems

In order to simulate the strong electrical connection, the connection transformer of 1050 kV/510 kV and the connection impedance of 0.05+j0.003 are added between the two voltage levels. The fault is located at the 1050 kV commutation bus at the low end of the inverter station. Three-phase grounding fault occurs in 3 s and lasts for 0.1 s. The implementation process is shown in Figure 5.

It can be seen from Table 1 that when there is an electrical connection between the two voltage levels, the AC system of the two hierarchies under the fault will be affected, and the degree of commutation failure will become more serious than that without electrical connection. However, under the control mode of adding recovery strategy, the number of commutation failures is significantly reduced, and the recovery speed is slightly faster than that of conventional control.

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**Figure 4.** Response of control strategy and DC system under permanent fault.
Conventional Control
Recovery Strategy Control

Figure 5. Response of control strategy and DC system under Instantaneous fault.

Table 1. System response of two modes when AC side electrical connection is strong.

| Variable                  | Fault happen | Failure recovery |
|---------------------------|--------------|-----------------|
|                           | Conventional | Recovery Strategy | Conventional | Recovery Strategy |
| $u_L$ (pu)                | 0            | 0               | 1            | 1               |
| $u_H$ (pu)                | 0.63         | 0.63            | 1            | 1               |
| Number of commutation failures ($c_L$) | 4 | 1 | 9 | 1 |
| Number of commutation failures ($c_H$) | 1 | 1 | 5 | 0 |
| Failure recovery time(s)  | ——           | ——              | 0.49         | 0.41            |

6. Conclusions
In this paper, a strategy of commutation failure control and recovery based on real-time fault detection and determination is proposed. A PSCAD/EMTDC model is built according to the actual parameters of a hierarchyed UHVDC transmission project at the receiving end. The conclusions are as follow:

- When serious transient faults occur in AC system and consecutive commutation failures are inevitable, the strategy proposed in this paper enables DC control system to start fast phase
shifting, reduces the number of automatic restart, and reduces the risk of continuous multiple commutation failures.

- When a permanent serious fault occurs in a single-hierarchy AC system, the strategy in this paper is to isolate the fault hierarchy commutation unit, avoid the outage of the whole HVDC transmission system, and prevent the non-fault hierarchy commutation unit from commutation failure repeatedly, so as to improve the reliability of transmission.

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