Analysis of the Effect of an AC Three-phase Fault on the Commutation Failure of DC Transmission System

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Abstract. In AC/DC interconnected systems, the commutation failure of the DC system caused by the AC-side fault is one of the common faults of the inverter. According to the actual engineering parameters, a detailed model of ±660kV Yindong DC transmission project was built using PSCAD/EMTDC simulation tools, and at the same time, an equivalent model of Shandong power grid on the inverter side was also established using physical equivalence-based equivalent methods. On this basis, a simulation analysis was made on the operation of the Yindong DC system when there was a three-phase symmetrical fault in the AC system, providing a reliable reference for the safe and stable operation of the Yindong DC transmission system and other HVDC transmission projects.

1. Introduction
Commutation failure is one of the most common faults in HVDC transmission systems. Commutation failure may reduce DC voltage and DC transmission power, increase DC current, shorten converter valve life, or cause DC bias of converter transformer or overvoltage of weak AC system on the inverter side [1-4]. In case of improper control, another commutation failure will occur following the previous one, eventually leading to the interruption of the DC transmission power[5-7]. Literature [8] analyzed main factors causing commutation failure, explained them with examples, and concluded that the commutation failure is the reaction of other faults in most cases. Literature [9] analyzed the impact of three-phase short-circuit faults in Shandong power grid on Yindong DC with the help of electromechanical transient simulation program PSS/E.

This paper, with the severest three-phase short-circuit fault in the AC system as an example, deduced the mathematical formula for the impact of AC system faults on the DC system from the definition of node self/trans-impedance, analyzed two main factors causing the commutation failure - the location and severity of the fault, and verified them by simulation in the established AC/DC model. This paper depicted the impact of AC-side faults on the commutation failure of the DC system from the grid structure, providing a theoretical basis for analyzing the commutation failure of the DC system.

2. Establishment of the system model

2.1. Yindong DC transmission system modeling
The converter transformer of the Yindong DC system adopts a single-phase dual-winding structure with a total of 12 main transformers. Each station is equipped with four smoothing reactors for each pole, including one on the polar line and three on the neutral line. Each pole is installed with two sets of double-tuned (6/42, 12/24) DC filters on each side. The Yindong DC system uses passive AC filters with a combination of single-tuned filters (HP3, HP12) and double-tuned filters (HP11/13, HP24/36). Considering the low impact of the DC line model on the simulation, the Bergeron line model is adopted. The main circuit structure of the system is shown in Figure 1.

![Figure 1. Schematic diagram of ±660kV Yindong HVDC transmission system](image)

2.2. Equivalent model of Shandong power grid AC system

This paper adopted a physical equivalence-based equivalent method and a power system analysis software package (PSASP) to perform proper dynamic equivalence of Shandong power grid. The grid data were sourced from Shandong power grid in a winter. For any node on the 500kV main network frame of the Yindong DC system, its standard structure after the equivalence is shown in Figure 2. During the dynamic equivalence, the system's 500kV main network frame and generator set with a larger generating capacity should be reserved.

The 500kV bus voltage and its equivalent generator output can be obtained from the power flow calculation data before the equivalence; the short-circuit current injected by the equivalent transformer when the 500kV bus is short-circuited can be calculated from the system's short-circuit current before the equivalence (i.e. the sum of short-circuit currents when the 500kV node is added to the 220k line before the equivalence); the sub-transient reactance $X'_{d}$ of the equivalent generator takes a typical value of 0.2 (based on its own capacity), ignoring the impact of the equivalent generator and transformer resistance; the static load characteristics show 50% constant power and 50% constant impedance, and considering the effect of constant power load namely induction motor on short-circuit current calculation, the sub-transient reactance $X''_{m}$ of the induction motor takes 0.18 (based on its own capacity). The circuit diagram during normal power flow calculation is shown in Figure 3.

![Figure 2. Chorogram based on physical equivalent method](image)

![Figure 3. Equivalent diagram of 500kV node after power flow calculation](image)
In Figure 3, $E_d''$ and $E_m''$ represent the sub-transient electromotive force of the equivalent generator and induction motor respectively; $X_d''$ and $X_m''$ represent the sub-transient reactance of the equivalent generator and induction motor respectively; $Z$ represents the equivalent impedance of constant impedance load; $X_t$ represents leakage reactance of the equivalent transformer.

According to the known data, values of $U_1$, $\theta_1$, and $X_t$ are obtained through a simplified calculation of the circuit diagram shown in Figure 3, and their simulation models are established using PSCAD/EMTDC. At the same time, in order to ensure the similar dynamic characteristics of the line before and after the equivalence, the AC transmission line adopts the Bergeron model, and the positive sequence resistance, positive sequence inductance and positive sequence capacitance per unit length of the line are input into the model according to the power flow calculation results.

3. Fault simulation analysis

In this paper, PSCAD/EMTDC electromagnetic transient simulation software was used to establish an equivalent model of AC/DC hybrid system including Yindong DC system and Shandong power grid, and simulation analysis was made on the basis of the established model. The fault was set as: 0.5s access fault, 0.55s fault clearance, and restarting the system to resume normal operation.

3.1. Impact of different fault severities on commutation failure

The fault location was selected on the Daze 500kV AC line which is close to the Qingdao converter station. Through experiments, the $Z_i/Z_b$ between the two nodes is equal to 1.48. When the voltage drop at this place is greater than about 153.92kV, the Yindong DC system will suffer a commutation failure, and the transition resistance at this time is approx. 40Ω. In order to further explain the impact of the fault severity on the commutation failure, the system response characteristics when the transition resistance is 0Ω, 30Ω, 40Ω, and 50Ω are given below:

![Waveforms of three-phase symmetrical short-circuit fault at 500kV line of Daze](image)

According to Figure 4, during normal operation, the DC current is stable at the rated value of about 3.03kA, the inverter-side DC voltage is about 630kV, the voltage loss is about 30kV, and the voltage loss rate is about 4.55%. The turn-off angle $\gamma$ on the inverter side is stable at around 17°, the active power from the inverter is about 3,800MW, the loss is about 200MW, and the line loss rate is about
5%. The above data are basically consistent with the operating conditions of the Yindong DC system project, thus proving the accuracy of the established model.

When a fault occurs at 0.5s, if the grounding resistance is 0Ω and 30Ω, the system commutation fails, the inverter's turn-off angle $\gamma$ quickly drops to 0, and the DC voltage, current, and transmitted power fluctuate greatly. At this time, the firing angle on the rectifier side can increase to 120° at most to make the converter running in the inverter state. This process is also called the gated phase shift (GS) process. Through this operation, converters at both ends work in the inverter state, enabling the energy in the DC circuit to be released into the AC network, and accordingly leading to the rapid attenuation of the DC current. In addition, due to the voltage dip of the DC line, the VDCOL of the control system on both sides works, reducing the current setting value and increasing the trigger delay angle, which is advantageous to the recovery of DC operation. After the fault is eliminated, the active power for DC transmission will be restored to the rated value within 0.3s. When the grounding resistance is 40Ω, the DC transmission system is at the risk of commutation failure, the inverter's turn-off angle $\gamma$ is equal to 8.12°, the commutating bus voltage is 0.897p.u, the DC power drops to about 2,400MW, and the active power loss is about 36.8%. When the grounding resistance is greater than 40Ω, the voltage, current, and extinction angle will change within a small range, and the DC system will not suffer the commutation failure.

3.2. Impact of electrical distance
When $Z_{ii}/Z_{ij}$ is less than about 5.05, the voltage drop at the commutating bus $j$ caused by the three-phase metallic short-circuit grounding at $i$ could cause the commutation failure of the DC system. According to the equivalent Shandong power grid structure diagram, the electrical distances between 500kV lines of Rizhao, Zaozhuang, Zouxian Power Plant and Liaocheng and Jiaodong converter station increase in turn, and are respectively 2.01, 3.85, 5.19, and 9.37 obtained through experiments; obviously, $Z_{ii}/Z_{ij}$ also increase in sequence. This indicates that a three-phase metallic short-circuit grounding fault on the 500kV lines at Rizhao and Zaozhuang will cause the commutation failure of the Yindong DC system, and a three-phase metallic short-circuit grounding fault on the 500kV lines at Zouxian Power Plant and Liaocheng will not cause the commutation failure of the Yindong DC system. Set up three-phase metallic short-circuit faults at these places in turn, and the response characteristics of the system are shown in Figure 5.
Figure 5. Waveforms of three-phase symmetrical short-circuit fault of 500kV line at different site

According to Figure 5, a three-phase fault in the 500kV lines at Rizhao and Zaozhuang which are close to the Yindong DC system will cause commutation failure of the DC system; a three-phase fault in the 500kV lines at Zouxian Power Plant and Liaocheng which are far away from the Yindong DC system will not cause the commutation failure of the DC system. In particular, the DC system will not be affected by any failure in 500kV line at Liaocheng. The shut-off angles on the inverter side of the DC system are 0°, 5.32°, 8.71° and 14.25° respectively. The simulation results are consistent with the previous theoretical derivations, which verify the accuracy of the method proposed in this paper.

4. Conclusion
The effect of AC symmetrical faults on the DC system was explained from a physical perspective. According to actual engineering parameters, an electromagnetic transient model of Shandong AC/DC hybrid power grid was established using the electromagnetic transient simulation software PSCAD/EMTDC, providing a basis for future analyses of AC and DC systems, and an effective research method for analyzing the operation of Shandong power grid after multiple DC feed-in.

Acknowledgments
We would like to express our gratitude to all those helped us during the writing and publish of this paper.

References
[1] Thio C. V., Davies J. B., Kent K. L. (1996) Commutation failures in HVDC transmission systems[J]. IEEE Trans on Power Delivery, 11: 946-957.
[2] Kristmundsson G. M. Carroll D. P. (1990) The effect of AC systems frequency spectrum on commutation failure in HVDC inverter[J]. IEEE Trans on Power Delivery, 5: 1121-1128.
[3] Wang G., Li Z., Huang M., Li H. (2010) Influence of initial fault voltage angle on commutation failure identification in a HVDC system. Automation of Electric Power Systems. 34: 49-54.
[4] Hao Y., Ni R. (2006) Analysis on influence factors of commutation failure in HVDC. High Voltage Engineering, 32: 38-41.
[5] Ci W., Liu X., LIU Yutian. (2011) Commutation failure simulations of ±660kV Yindong-Jiaodong HVDC line. Power System Protection and Control, 39: 134-139.
[6] Liu Y., Li X., Cai Z. (2010) Location of HVDC converter grounding fault. Automation of Electric Power Systems, 34: 86-91.
[7] Xu Z., Yang J., Duan H. (2007) An equivalent reduction method for electromagnetic transient simulation of large-scale power systems. Southern Power System Technology, 1: 37-61.
[8] Jing Y., Ren Z., Ou K. (2004) Impact on HVDC communication failure of AC single phase fault. High Voltage Technology, 30: 60-62.
[9] Ren J., Li X., Jin X., et al. (2008) Simulation study on commutation failure caused by switching AC filters of inverter stations in multi-infeed HVDC system. Power System Technology, 32: 17-22