A new method of converter transformer protection without commutation failure

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Abstract. With the development of AC / DC hybrid transmission technology, converter transformer as nodes of AC and DC conversion of HVDC transmission technology, its reliable safe and stable operation plays an important role in the DC transmission. As a common problem of DC transmission, commutation failure poses a serious threat to the safe and stable operation of the power grid. According to the commutation relation between the AC bus voltage of converter station and the output DC voltage of converter, the generalized transformation ratio is defined, and a new method of converter transformer protection based on generalized transformation ratio is put forward. The method uses generalized ratio to realize the on-line monitoring of the fault or abnormal commutation components, and the use of valve side of converter transformer bushing CT current characteristics of converter transformer fault accurately, and is not influenced by the presence of commutation failure. Through the fault analysis and EMTDC/PSCAD simulation, the protection can be operated correctly under the condition of various faults of the converter.

1. Introduction
With the "west to East, North South mutual supply, full implementation of the development strategy of national network of power grid, the DC transmission mode, the working mechanism, operation mode, fault characteristics and the traditional AC power systems have great differences\textsuperscript{[1]}. In AC / DC hybrid system, converter transformer and converter are nodes that can realize switching between AC and DC in power system, and its reliable and safe operation is the basis of safe and stable operation of HVDC system.

At present, converter transformer protection is current differential protection. Because the converter is a nonlinear element, for the AC side, harmonic current is the main source of the converter transformer differential protection under normal conditions subjected to harmonic current is large, resulting in great influence on the inrush current and TA transformer saturation criterion\textsuperscript{[2]}. At the same time, AC system fault has led to a decreasing voltage and an imbalancing current, which easily trigger DC protection misoperation, resulting in DC locking and other accidents\textsuperscript{[3]}. After commutation failure, the short circuit current equivalent AC current and pure AC system into the AC side of HVDC system has different...
characteristics, namely, the amplitude and phase fluctuations, the distortion of the above fault characteristics impact on differential protection, may cause internal fault system momentum larger than movement, causing misaction. At the same time, due to the failure of the AC system on both sides of the system, the differential protection of the converter and the differential protection of the converter only meet the time limit, but there is no coordination between the setting values, When AC and DC transient intrusions occur, may cause uncertainty between converter protection and converter transformer protection [4]. It is necessary to carry out the overall protection and performance analysis of the two components.

According to the commutation relation between the AC bus voltage of converter station and the output DC voltage of converter, defines the generalized ratio and proposes a new method of converter transformer protection based on generalized ratio. The method uses online monitoring based on generalized ratio for the abnormal or fault of converter element, and accurate fault diagnosis of converter transformer is carried out by utilizing the CT current characteristic of converter transformer valve side bushing, it also solves the problem that the differential protection of converter transformer has been affected by commutation failure for a long time, resulting in refusal or malfunction.

2. The Mechanism of Commutation Failure And Its Influence On Differential Protection

2.1. The Mechanism of Commutation Failure
In the multi-feed DC transmission system stable operation, if the AC system short circuit failure, it may cause the fault point near the inverter station commutation failure; the commutation failure of the DC system is explained by the six-leg commutation circuit. After the commutation of the upper and lower arms is commuted, the internal current of the converter valve whose end is turned on is not extinguished to 0 or when the converter valve is subjected to the reverse voltage If the commutation process is not completed at the end of the commutation process, if the applied voltage is positive, the converter valve is switched on again and the phase change occurs. At this time, the commutation circuit is internally short-circuited so that the converter valve Off, commutation process failed to complete, this phenomenon is called commutation failure.

2.2. The effect of commutation failure on traditional protection
DC system protection is designed based on a security constraint (device attribute) of a safety device that protects a device, and its principles, logic and value of the power grid operation of the complexity and coordination with the lack of consideration. After commutation failure, the equivalent frequency current of the DC system into the AC side has different characteristics from the short circuit current of the pure AC system, that is, the amplitude decreases and the phase angle fluctuates, the distortion of these fault characteristics has an impact on differential protection, the system may cause more than the amount of action during the zone failure, triggered protection against motion.

3. A New Method for Converter Transformer Protection
Three phase bridge rectifier circuit based on 12 pulse thyristor thyristor element, the relationship between the DC voltage of converter outlet \( U_d \) and the valve side voltage of converter transformer \( U_2 \) can be obtained, Such as formula (1), formula (2) and formula (3).

\[
U_d = 2 \times \frac{\pi}{3} \left( \frac{2\pi + \alpha}{3} \right) \sqrt{6U_{2a} \sin \omega t \cos \alpha} = 2 \times 2.34U_{2a} \cos \alpha
\]  

(1)

\[
U_d = 2 \times \frac{\pi}{3} \left( \frac{2\pi + \alpha}{3} \right) \sqrt{6U_{2b} \sin \omega t \cos \alpha} = 2 \times 2.34U_{2b} \cos \alpha
\]  

(2)
\[ U_d = \frac{1}{3} \int_0^{2\pi+\alpha} \sqrt{6U_{2c}\sin\omega t} dt = 2*2.34U_{2c}\cos\alpha \]  

(3)

Where \( \alpha \) is the converter conduction angle.

Define the commutator area for the converter transformer and the converter as a whole. In the case of non-internal fault, the ratio of the primary voltage \( U_1 \) of the converter transformer to its secondary voltage (valve side voltage) \( U_2 \) is equal to the transformer ratio \( K_T \), as shown in equations (4), (5) and (6).

\[
K_{Ta} = \frac{U_{1a}}{U_{2a}} \quad \text{(4)}
\]

\[
K_{Tb} = \frac{U_{1b}}{U_{2b}} \quad \text{(5)}
\]

\[
K_{Tc} = \frac{U_{1c}}{U_{2c}} \quad \text{(6)}
\]

In the case of non-internal failure of the commutation area, by formula (1) ~ (3), type (4) ~ (6) can be obtained, the relationship between the primary voltage \( U_1 \) of the converter transformer and the DC voltage \( U_d \) of the converter outlet is shown in formula (7), formula (8), and (9).

\[
\frac{U_{1a}}{U_d} = \frac{K_{Ta}}{2*2.34*\cos\alpha} \quad \text{(7)}
\]

\[
\frac{U_{1b}}{U_d} = \frac{K_{Tb}}{2*2.34*\cos\alpha} \quad \text{(8)}
\]

\[
\frac{U_{1c}}{U_d} = \frac{K_{Tc}}{2*2.34*\cos\alpha} \quad \text{(9)}
\]

Order \( K = \frac{U_1}{U_d} \), \( K \) is defined as generalized ratio.

When an external fault occurs in the converter zone, considering the actual operation of UHVDC transmission system \( a = 0 \), the generalized transformation ratio \( K \) is constant, expressed as \( K_c \), as shown in equation (10).

\[
K_c = \frac{U_1}{U_d} = 0.660 \quad \text{(10)}
\]

Similarly, the generalized transformation ratio of low voltage bridges can be obtained.

\[
\delta = \frac{U_{1a} - KU_d}{U_1} \quad \text{(11)}
\]

\[
\delta = \frac{U_{1b} - KU_d}{U_1} \quad \text{(12)}
\]
Based on KCL, when the normal operation of the converter zone or external faults (except for the converter outlet fault), since formula (10) has always been established, $U_1 = K \cdot U_d$, then $\delta$ is approximately zero.

When the converter area outlet fails, since $U_d$ is reduced to zero will lead to equation (10) does not valid, But from the formula (11) ~ (13) available at this time $\delta = 1$.

According to the above analysis, using the size of the integrated error $\delta$ can correctly determine the internal and external failure of the commutation zone.

Considering the current transformer error, and when calculating converter transformer, the leakage reactance is neglected and the voltage drop is generated, $h_1 = 0.1$.

As shown in figure 2, $I_d$ is the CT current of the valve side bushing of the converter transformer, when the converter is in normal operation, $I_d$ is the sum of current of common cathode and common anode converter valve group. When the Y / Y converter transformer fails, $I_d$ is only the common cathode group converter valve current, that is half of the rated current; and when the converter transformer fails, $I_d$ is several times or even ten times of the rated current.

Therefore, the $I_d$ size can be used to locate the fault components accurately, if it is satisfied equation (14) ~ (16), then the flow transformer failure, otherwise, there is a fault outside the converter transformer area.

$$I_d < h_2$$

$$I_d < h_2$$

$$I_d < h_2$$

$H$ is usually taken as the rated current in engineering.

The principle block diagram is shown in figure 1.

![Figure 1. Protection logic scheme.](image-url)
4. Analysis of the Effect of Commutation Failure on the New Protection Algorithm of Converter Transformer

Fig. 2 is the schematic diagram of the AC / DC hybrid system. When the AC-DC hybrid system in the AC system that is the AC transmission line failure will lead to AC bus voltage drop, it is not possible to provide commutation voltage for the inverter in the inverter station and the inverter station will fail. When commutation fails will lead to lower DC voltage, DC current increases, DC system transmission power decreases, however, there is no failure inside the converter station, the commutation relationship between the converter DC voltage Ud and the converter-side voltage U2 is still established, the definition of the generalized ratio is still fixed. So the resulting error is approximately zero, it is determined that no failure has occurred inside the commutation zone.

Figure 2. AC and DC hybrid system schematics

Inverter station is in the worst state of the converter commutation failure at the same time inside the converter station failure. Fig. 3 is a schematic diagram of a failure occurring at the same time as a commutation failure. When the AC-DC hybrid system in the inverter station commutation failure, while the inverter station also fails, the commutation relationship between the inverter DC voltage Ud and the converter-side voltage U2 is not established and the generalized ratio is no longer fixed. The resulting error is between 0 and 1, it was determined that a failure occurred inside the commutation zone. Further, the current measured by the valve side sleeve CT of the converter transformer is used for fault location.

Therefore, when the AC system in the AC / DC hybrid system fails cause the commutation failure, integrated protection algorithm for converter station can also be applied to inverter station. It can correctly distinguish whether the converter area is out of order or the location of the fault, reliable removal of the fault and avoid damage to the converter equipment, at the same time improve the reliability of power supply.

Figure 3. A schematic diagram of a failure occurring at the same time as a commutation failure

5. Simulation Verification

Using PSCAD simulation software to build the simulation model of ± 800kV bipolar DC transmission system shown in Fig.4. The control system reference model mainly includes constant current control, constant voltage control and fixed power control. In this paper, the length of the window is selected as 5ms, which can ignore the influence of the control system[6]. The transmission power is 2500MW, rated current is 3.125kA, the conveying distance is 2000km, two pole DC lines are joined by the same pole, DC transmission lines using 6 split steel core aluminum wire, the rated cross sectional area is 630mm*mm, R = 14.97 ohm. Voltage drop calculation of transmission line: \( \Delta U = I_n R = 3.125 \times 14.97 = 46.78 \text{ kV} \). The failure time is 0.76s. In this paper only gives the A-phase simulation results.
5.1. Inverter station commutation failure but no failure
When AC / DC hybrid system commutation failure occurs at 1s, the DC voltage and the AC voltage amplitude of the inverter side will decrease, the generalized ratio k is about 0.6 and the combined error is approximately zero, current Id is about 5A, it is determined that the converter station has not failed.

5.2. Commutation failures and faults occur simultaneously in the inverter station
When the AC-DC hybrid system in the AC line three-phase failure caused commutation failure, at the same time, the converter in the converter station also fails, as shown in Figure 4, converter current DC voltage Ud (shown in the figure voltage curve dotted line) and the converter transformer primary voltage U1 (solid line shown), the integrated error δ and the converter transformer valve side casing CT current Id, the protection of the action output signal are given. From figure 5 we can see when the system commapses at 1.5s, the duration is 0.5s, which would degrade the amplitude of the AC voltage U1 and the DC voltage Ud, The integrated error δ is between 0 and 1, Id value is reduced to half of the original. The protection can be reliably operated after the fault has occurred.

![Figure 4. DC transmission system commutation failure](image)

![Figure 5. Commutation failure while the converter transformer also fails](image)

6. Conclusion
In this paper, according to the commutation relationship between the exchange station AC bus voltage and inverter output DC voltage, the CT current characteristics of the valve side casing of the converter transformer I have put forward a new method of integrated protection for converter stations based on generalized transformation ratio. This method can be used for accurate positioning of faulty components. A large number of simulation results show that: the method is simple and fault characteristics are obvious. In various operating conditions protection can be fast, sensitive, reliable action. It is possible to improve the power supply reliability of the special DC transmission system.
References
[1] LI Xiaohua, CAI Zexxiang, HUANG Minghui, et al. Transient power converse in an AC/DC interconnected power grid[J]. Automation of Electric Power Systems, 2012, 36(10): 61–66.
[2] QIAO Xiaomin, CAI Zexxiang, Wen Jun. Influence of converter transformer differential protection by harmonic in HVDC transmission system[J]. Power System Protection and Control, 2009, 37(10): 111-114.
[3] LI Jiaman, CAI Zexiang, LI Xiaohua, et al. Response Mechanism of UNVDC System Protection to Faults in UHVDC System and Analysis on Malfunction of UHVDC Protection Caused by Faults in UHVDC System[J]. Power System Technology, 2015, 39(4): 953–960.
[4] XU Min, CAI Zexiang, HAN Kunlun, et al. Influence Analysis of AC System Transient Invasion on DC Protective Relaying in AC/DC Hybrid Power System[J]. High Voltage Engineering, 2014, 40(11): 3618-3625.
[5] HU Jing, ZHAO Chengyong, ZHAO Guoliang, et al. System Architecture of a Universal Integrated Control and Protection Platform for Converter Stations[J]. Proceeding of the CSEE, 2012, 32(22): 133-140.
[6] SHU Hongchun, ZHANG bin, ZHANG Guangbin, et al. Identification of Lightning Disturbance in UHVDC Transmission Lines Using Extension Theory[J]. Proceeding of the CSEE, 2011, 31(7): 102-111.