Analysis and Verification of Differential Protect Operation of AC / DC Hybrid Power

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Abstract. In this paper, the characteristics of AC / DC hybrid faults are analyzed, and the influence of AC / DC hybrid power system on AC current differential protection is analyzed and discussed. When the DC commutation fails, the power frequency current injected into the AC power grid is ahead of its voltage. At this time, the phase angle between the power frequency current and the voltage will change, which will cause the action of the AC line fault. If the current decreases, the brake current will increase, as a result, differential protection refused to action. The PSCAD is used as the platform to simulate the differential protection operation. And the parameter identification based transmission line protection with shunt reactors is proposed. Simulation results show the correctness of the theoretical analysis.

Introduction

High-voltage direct current transmission (HVDC), which is free from inductive reactance and capacitive reactance and has no synchronization problems, enables long-distance transmission, asynchronous network interconnection, and large-capacity transmission[1-3]. At present, China's AC-DC hybrid grid pattern has been gradually formed. However, in the AC / DC hybrid system, there are many new electrical fault characteristics, which will make the relay protection in the pure AC power grid challenged, thus the power grid safety and stability have a significant impact, for instance, AC and DC hybrid power grid which appeared in the commutation failure and transient power back problems will lead to relay protection malfunction and refuse to move[4-5]. When multiphase failure of the close electrical distance occurs in the commutation or AC system failure occurs, it will result in the risk of uncertain actions, and therefore we need to pay attention to such issues and analysis.

Current differential protection by comparing the current vector at both ends of the line is to determine the internal fault or the external fault. In the AC / DC hybrid network, in order to make the safe and stable operation of the AC / DC hybrid power grid, it is very important to analyze the operation characteristics of the current differential protection of the DC transmission line. In this paper, the current differential protections of the pure AC system and AC / DC hybrid system are analyzed by using current differential protection. The PSCAD / EMTDC is used as the simulation platform to verify the differential protections.

Analysis of the Effect of AC / DC Hybrid System on Current Differential Protection

The current from DC system into the AC grid can be regarded as the equivalent power frequency current, because the AC power grid failure can cause DC commutation failure. If DC commutation fails, the equivalent power frequency current into the AC power grid is ahead of its voltage, and in pure AC power grid, the power supply voltage is ahead of short-circuit current. Therefore, for the line current differential protection, it will have a certain impact.

To AC-DC hybrid power grid system, at point f, take a phase single-phase ground fault as an example. As is shown in Figure 1, under the condition of commutation failure, the equivalent power
According to the diagram and the differential protection fault criterion, the criterion of phase current differential protection fault component can be obtained as follows:

\[ \Delta I_{a1,d} = |\Delta I_{a1,M} + \Delta I_{a1,N}| = |\Delta I_{a1,f} - \Delta I_{a1,eq,f}| \]  
(1)

\[ \Delta I_{a1,x} = |\Delta I_{a1,M} - \Delta I_{a1,N}| = |\Delta I_{a1,f} + (\Delta I_{a1,eq,M} + \Delta I_{a1,eq,N})| \]  
(2)

\( \Delta I_{a1,d} \) and \( \Delta I_{a1,x} \) are respectively the actuating quantity and restraining quantity of the current system under the influence of commutation failure of a phase fault component current differential protection. \( \Delta I_{a1,f} = \frac{\Delta E_f}{R_f + Z_N + Z_x} \); \( \Delta I_{a1,eq,M} \), \( \Delta I_{a1,eq,N} \), \( \Delta I_{a1,eq,f} \) are respectively the shunt of \( \Delta I_{a1,eq} \) on both sides of the line and at the point of failure. In the case of commutation failure, \( \Delta I_{a1,eq} \) lags behind \( \Delta U_{busa} \), and after the angle in the vicinity of 90 degrees.

As in the pure AC system which is generally \( \Delta I_{a1,f} \) lagging \( \Delta U_{busa} \) behind close to 90 degrees, so the presence of \( \Delta I_{a1,eq} \) will cause the action current decreases, increasing the braking current. It will affect the current differential over-protection of the operating characteristics, which may cause differential protection of the refusal. For the current differential steady-state component criterion, the load current is twice as large as the fault component criterion in the braking current. The influence of the fault component criterion is greater than the influence of commutation failure of the DC system.

In addition, it can from another point of view on the AC-DC hybrid power system to analyze the impact of current differential protection, as is shown in Figure 3.

Figure 3 is a simplified AC-DC hybrid power grid system diagram, this diagram will be AC-DC hybrid power grid divided into three parts, namely, HVDC system, AC system 2 and AC system 1.

Considering the DC system as an external fault source and analyzing only the power frequency, the whole receiving end network can be regarded as the advanced network. So we decompose the DC system into three kinds of system stacks as is shown in Figure 4 to further analysis.
From the superposition of equivalent circuit in Figure 4 available:

\[
\Delta I_d = \Delta I_m + \Delta I_N = \frac{\Delta u|_{lo}}{R_g + Z_{SN} + Z_{LN}} \\
\Delta I_r = \Delta I_m - \Delta I_N = \frac{2R_g \Delta I_{dc.eq} - \Delta u|_{lo}}{R_g + Z_{SN} + Z_{LN}}
\]

According the format(3), under the form of the fault, the amount of action is relatively stable and less volatile; under the circumstances of failure in the exchange side without the failure of the transient process, the previous Angle"\( \Delta I_{dc.eq} \), \( U_1 \) is generally less than 90, in addition to the rotation \( \Delta I_{dc.eq} \) with \( \Delta I_{dc.eq} \) the counterclockwise process will become larger, so the restraining quantity will gradually become larger, once the restraining quantity is greater than the actuating quantity, it will lead to relay protection refusal.

On the other hand, from the perspective of the steady-state quantity of the current differential protection effect analysis. According to the fault analysis theory, the steady state quantity is composed of the sum of the fault component and the load component. In this case, the amount of steady-state operation is the same as that of the fault component, but the amount of restraining quantity is increased by a factor of two. The dynamic differential protection based on steady-state is expressed as

\[
|\Delta I_m + \Delta I_N| \geq k_1 |\Delta I_m - \Delta I_N + 2I_L|
\]

Compared with the fault component criterion, the steady-state quantity criterion increases \( 2I_L \) in the restraining quantity. At this time, the load current can greatly increase the restraining quantity, and it is easy to cause the restraining quantity to be larger than the actuating quantity, causing the miss trip of the relay protection.

To sum up, from the perspective of differential protection, AC-side power grid failure can lead to DC commutation failure, which has an impact on the protection of AC power grid. In particular, due to the commutation failure, the equivalent power current frequency and its voltage angle from DC system into the AC power grid can change, which will cause the incorrect action of AC power grid differential protection.

**Simulation and Verification of Incorrect Operation of Current Differential Protection**

According to the principle of current differential protection, differential protection action equation is \( |I_m + I_n| - K |I_m - I_n| \geq I_{opo} \) .According to the formula, we can establish logic criterion of differential protection. In simulation, in order to more intuitively reflect the influence of power frequency current and voltage phase angle changes on the exchange side of the differential protection, let the AC power grid into the current frequency and voltage angle be 0. At this point the simulation can be obtained at both ends of the fault current \( I_{an} \), and \( I_{am} \)at this time according to build the logic of the criteria obtained\( F_{ina} \). According to the formula\( |I_m + I_n| - K |I_m - I_n| \geq I_{opo} \) If the output \( F_{ina} \) is 1at this time, it will meet the requirement of protection. If the output is 0,
Protection will not take into effect. The fault is set at 1s for a duration of 0.2s. Then when the current frequency of the AC power grid and voltage angle is 0, then the images are as shown below.

![Figure 5. waveform $I_{am}$](image1)

![Figure 6. waveform $E_{am}$](image2)

If at this time we change the phase angle of power frequency current into the alternating current power grid and voltage, the phase angle is reversed to 180, at this point, the situation is as shown below.

![Figure 7. waveform $I_{am}$](image3)

![Figure 8. waveform $E_{am}$](image4)

It can be seen from the figure above that when the current and voltage angle injected into the AC side are changed, that is, if the power frequency current injected into the AC power grid is ahead of the voltage, the differential protection of the AC side will be rejected. The simulation results are verified.

**Improvement Measures for Current Differential Protection**

In order to overcome the adverse effect of transient process on line differential protection, a pilot protection based on parameter identification for the transmission line with shunt reactors is proposed. The parameter identification of the transmission line longitudinal protection is by identifying the internal and external fault model parameters to distinguish internal fault and external fault.

**Principle and Criterion of Pilot Protection for Parameter Identification**

Take the single-phase line as an example, when the external fault occurs, the fault component network is shown in Fig 9.

![Figure 9. Fault component network for external faults.](image5)
Assuming that the direction from the bus bar to the bus bar to be protected is the positive direction of the current, the currents flowing through the current chokes are $\Delta i_m$ and $\Delta i_n$ whereby the voltage across the system can be obtained as follows:

$$
\begin{align*}
\Delta u_m &= L_m \frac{d\Delta i_{Lm}}{dt} + R_L \Delta i_{Lm} \\
\Delta u_n &= L_n \frac{d\Delta i_{Ln}}{dt} + R_L \Delta i_{Ln}
\end{align*}
$$

(6)

Among them, $R_L$ is the resistance of the parallel reactor, $i_L$ is the equivalent inductance of the parallel reactor. From (6) and Kirchhoff current law available external fault model formula is as follows:

$$
\Delta u_{cd} = L_L \frac{d\Delta i_{cd}}{dt} + R_L \Delta i_{cd}
$$

(7)

Thus, the external fault model is actually a shunt reactor model.

The fault component network for an internal fault is shown in Fig 13.

![Figure 10. Fault component network for internal faults.](image)

The voltage across the system is given by:

$$
\begin{align*}
\Delta u_m &= -L_m \frac{d\Delta i_{Lm}}{dt} - R_m \Delta i_{Lm} \\
\Delta u_n &= -L_n \frac{d\Delta i_{Ln}}{dt} - R_n \Delta i_{Ln}
\end{align*}
$$

(8)

Where, $I_{m}, I_{ns}$, and $R_{ms}, R_{ns}$ are the inductance and resistance of the system impedance at both ends of the line, respectively. (8) can be obtained by adding the two types of internal fault model formula is as follows:

$$
\Delta u_m + \Delta u_n = -L_{seq} \frac{d(\Delta i_m + \Delta i_n)}{dt} - R_{seq} (\Delta i_m + \Delta i_n)
$$

(9)

Among them $k_m = \Delta i_m/(\Delta i_m + \Delta i_n)$; $k_n = \Delta i_n/(\Delta i_m + \Delta i_n)$. In the high-voltage grid, the distribution coefficient of the fault component network can be seen as a real number, that is, $\Delta i_m$ and $\Delta i_n$ can be seen as the same phase, so $k_m$ and $k_n$ are real. $L_{seq}$ is the equivalent inductance. $R_{seq}$ is the equivalent resistance. As the impedance of the two terminal system is far less than the equivalent capacitive reactance of line distributed capacitance, the current of system impedance is much larger than the distributed capacitance current. Equation (9), $\Delta u_{cd} = \Delta u_m + \Delta u_n, \Delta i_{cd} = \Delta i_m + \Delta i_n - (\Delta i_m + \Delta i_n)$ then, the internal fault model formula is:

$$
\Delta u_{cd} = -L_{seq} \frac{d\Delta i_{cd}}{dt} - R_{seq} \Delta i_{cd}
$$

(10)

From (10), the internal fault model is actually the equivalent model of the two terminal system impedance. By comparing equations (7) and (10), it can be found that the external fault model and the internal fault model have the same form, so that their same form can be written as:

$$
\Delta u_{cd} = L_L \frac{d\Delta i_{cd}}{dt} + R_L \Delta i_{cd}
$$

(11)

(11) can be used to calculate the model parameters, and set the identification of inductive reactance:

$$
X_L = 2\pi f L, f = 25Hz
$$

(12)
In the internal fault, $X_L$ is equivalent to the inductive reactance of the two-terminal system and it is a small negative number. However, in the external fault, the inductive reactance of the shunt reactor $X_L$ is a big positive number. Therefore, it can be judged by the symbol and the size of the things that occurred at the time of internal or external fault.

**Simulation Verification**

By using the differential protection principle of parameter identification, $X_{LA}$, $X_{LB}$, $X_{LC}$ represents the A, B, C respectively, phase inductance to identify the inductive reactance setting $X_{set}$. From Table 2, when the internal fault occurs, the identification of non-fault phase inductive reactance at this time more than 1000Ω, while the fault phase is negative, about dozens of ohm. The difference between the internal fault and the external fault is obvious at this time, the protection will not be affected by the transition resistance.

<table>
<thead>
<tr>
<th>Fault type</th>
<th>/</th>
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<tbody>
<tr>
<td>K1 AG</td>
<td>0</td>
<td>-49</td>
<td>1467</td>
<td>1873</td>
<td>600</td>
</tr>
<tr>
<td>K1 BC</td>
<td>0</td>
<td>1596</td>
<td>-107</td>
<td>-78</td>
<td>600</td>
</tr>
<tr>
<td>K1 ABG</td>
<td>0</td>
<td>-95</td>
<td>-84</td>
<td>1265</td>
<td>600</td>
</tr>
<tr>
<td>K1 ABC</td>
<td>0</td>
<td>-137</td>
<td>-107</td>
<td>-99</td>
<td>600</td>
</tr>
<tr>
<td>K3 AG</td>
<td>150</td>
<td>-61</td>
<td>1761</td>
<td>1620</td>
<td>600</td>
</tr>
<tr>
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<td>-43</td>
<td>1592</td>
<td>162</td>
<td>600</td>
</tr>
<tr>
<td>K4 AG</td>
<td>0</td>
<td>1148</td>
<td>1705</td>
<td>1602</td>
<td>600</td>
</tr>
</tbody>
</table>

In summary, the theory based on the principle of parameter identification of the pilot protection is to use the difference between the parameters of the fault models to distinguish internal and external fault. The method can not be affected by the fractional harmonics and the non-periodic components, which can improve the performance of line protection in AC / DC hybrid power systems, effectively solving the problem of line differential protection in high resistance grounding, DC system commutation failure, external fault and other failures, decreases in the sensitivity or reliability and so on.

**Conclusion**

As for AC and DC transmission mode, there are some differences between pure AC systems in the failure of electrical characteristics, working mechanism and mode of operation, affecting the AC and DC power grid in which the current differential protection incorrect. Through the analysis of this paper, we can get the following conclusions: 1) This paper analyzes the particularity of AC / DC hybrid power system and its particularity to the differential protection characteristic of AC / DC hybrid power system. 2) Based on the theoretical analysis, the PSCAD is used as the simulation platform to simulate the AC differential protection. The results verify the correctness of the theory. 3) Based on the analysis of the incorrect operation of current differential protection, the differential protection of transmission lines with parallel reactors based on parameter identification is proposed to verify its accuracy by recognizing the differences between internal and external fault model parameters.

**References**


