A Novel Protection Scheme for Outgoing Line Fault of AC Transmission Line near the Inverter Station of AC/DC Hybrid Power Grid based on AC Filter Characteristics

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Abstract—Compared with traditional AC power grid, the fault characteristics of the AC/DC hybrid power grid are more complex and variable. Hence there is a problem of incorrect action for the fault detection elements used in traditional AC power grid which comes up when an outgoing line fault occurs on the AC transmission line in the vicinity of the inverter station. To distinguish the fault direction under the aforementioned situation, a directional protection scheme based on the characteristics of the AC filter is proposed in this paper. Considering the information can be measured by AC line relay, a method for estimating the current provided by the AC filter is given during an outgoing line fault. According to the difference of current characteristics between forward and reverse fault, the fault direction can be judged based on waveform similarity among the currents provided by the AC filter and measured by the AC line relay. Finally, a simulation model is built on the PSCAD/EMTDC platform for extensive performance evaluation. The reliability and effectiveness of the protection scheme are verified under different cases.

1. Introduction

With the continuous development of the power system and the rapidly rising proportion of new energy sources on the grid, the operation of AC and DC hybrid power grids has become more and more common. As a key component of the AC/DC hybrid power grid, unlike traditional AC sources, converter station contains large numbers of power electronic devices, hence its fault characteristics are nonlinear and time-varying. Therefore, original AC line protections are facing many problems when applied to the AC/DC hybrid power grid [1].

Generally, power-frequency fault component based distance protection is configured in AC power grid to distinguish the direction of the outgoing line fault quickly. However, when an outgoing line fault occurs on the AC line in the vicinity of the AC/DC hybrid power grid, commutation failure is prone to happen. During the commutation failure, the characteristics of the DC power source will change, harmonic and non-periodic components will be injected into the AC grid through the inverter station as well, which is likely to cause incorrectly action of the power-frequency fault component based distance protection [2, 3].

Aiming to deal with problems above, a large number of scholars have proposed many different solutions to determine the fault direction of the AC line near the inverter station. According to the difference between the fault current provided by the AC and DC power sources, reference [4] offers a
new method of identifying the fault direction using correlation coefficients of measured voltage drop and calculated voltage drop, which is based on the R-L line model. Reference [5] takes synchronous squeeze wavelet transform for signal process, and gives a novel scheme to judge the fault direction by analyzing the energy of the transient fault current. However, it requires a lot of calculations. Reference [6] proposes a method to identify the fault direction based on the 0-mode voltage and current, but it does not make specific analysis and verification for the outgoing line fault scenario.

In this paper, a novel directional protection scheme is proposed. When a forward fault occurs on the AC line close to the HVDC installation, the current that AC line relay measures contains the current component provided by AC filter. Based on that, the fault direction can be determined by the current waveform similarity between the current measured by AC line relay and provided by AC filter. Extensive simulation results demonstrates that the proposed protection scheme can detect the fault direction rapidly and reliably, and will not be affected by fault time, fault types as well.

2. Analysis of Outgoing Line Faults on AC Lines

The structure of the inverter side of a typical AC/DC hybrid system is shown in Fig. 1. The inverter station and the AC system are connected to the bus, and the bus is equipped with AC filters and reactive power compensation devices. The AC system is connected to a single-circuit transmission line, and AC line protection devices are installed on both sides of the line. When there is only one transmission line on the AC side, the difference of the fault characteristics between the AC/DC hybrid system and the traditional AC system is the biggest, and the adaptability of the directional elements used in traditional AC system is the worst. Therefore, take the case of a single outlet on the AC side as an example for analysis.

The reference direction of each current in the AC/DC hybrid system is shown in Fig. 2. In Fig. 2, $i_{rp}$ represents the current provided by the reactive power compensation device, $i_{f}$ represents the current provided by the AC filter, and $i_{dc}$ represents the current provided by the DC source, $i_{m}$ represents the current measured by the AC line protection, and $i_{ac}$ represents the current provided by the AC source.

When a forward fault ($F_1$) occurs, for the AC line protection device on the converter bus side, there are
When a reverse fault \(F_2\) occurs, for the AC line protection device on the converter bus side, there are

\[
i_m = i_p + i_f + i_{dc}
\]  

(1)

Obviously, when an outgoing line fault occurs at the AC line near the inverter side, regardless of whether the fault is a forward fault or a reverse fault for the AC line protection, the AC filter will discharge to the fault point, and the discharge current is \(i_f\). The difference is that when a forward fault occurs, the discharge current \(i_f\) will flow through the AC line protection measurement; when a reverse fault occurs, the discharge current \(i_f\) will not flow through the AC line protection measurement.

In summary, it can be known that the fault direction can be judged by identifying whether the AC filter discharge current \((i_f)\) is contained in the current measured by AC line protection \((i_m)\). When an outgoing line fault occurs at the AC line near the inverter station, the voltage of the converter bus will drop greatly. The adjustment of the DC side control system has a certain time delay. Therefore, the discharge current of the AC filter will be much higher than the fault current provided by the DC side in a short time after the fault. By comparing the waveforms of \(i_m\) and \(i_f\), the criterion can be formed.

3. Criterion Realization

3.1. Calculation of the discharge current of AC filter

In order to compare the waveforms of the AC line measured current and the AC filter current, it is necessary to calculate the discharge current of the AC filter based on the electrical quantity of the AC line measurement. Take the second-order high-pass filter as an example, and its typical circuit structure is shown in Fig. 3. In Fig. 3, \(R\), \(L\), and \(C\) represent the resistance, inductance, and capacitance of the AC filter, respectively. When a metallic outgoing line fault occurs at the AC line, it is equivalent to a circuit change for the AC filter, and the discharge current of the AC filter can be obtained through the Laplace transform as shown in equation (3).

\[
i = -e^{-\alpha t} (A \cos \omega t + B \sin \omega t)
\]  

(3)

and \(A\), \(B\), \(\alpha\), \(\omega\) can be calculated as follows:

\[
A = \frac{u(0^-) + Ri(0^-)}{R}, \quad B = \frac{(R - \alpha L)u(0^-) - \alpha RL i(0^-)}{\omega RL}
\]  

(4)

\[
\alpha = \frac{1}{2RC}, \quad \omega = \sqrt{\frac{1}{LC} - \frac{1}{4R^2C^2}}
\]  

(5)

where \(u(0^-)\) and \(i(0^-)\) respectively represent the initial value of voltage and current at the moment of the fault.

The initial values of voltage and current at the moment of the fault can be obtained through iteration using the electromagnetic transient circuit of the AC filter shown in Fig. 4 and the electrical
quantities of the AC line during the two cycles before the fault. In Fig. 4, $u$ and $u'$ are node voltages, $R_C$ and $R_L$ represent the iterative equivalent resistances of inductance and capacitance respectively, which can be calculated according to equation (6), $I_C(t-\Delta t)$ and $I_L(t-\Delta t)$ represent the iterative equivalent current sources of inductance and capacitance respectively. In normal operation, most of the voltage drop of the AC filter is on the capacitive element. Therefore, set the initial value of $u'$, $I_C(t-\Delta t)$ and $I_L(t-\Delta t)$ to 0, and then obtain the discharge current iteratively according to equation (7) and equation (8).

$$R_c = \frac{\Delta t}{2C}, \quad R_L = \frac{2L}{\Delta t}$$

$$I_C(t-\Delta t) = I_C(t-2\Delta t) + \frac{2}{R_C}u_C(t-\Delta t)$$

$$I_L(t-\Delta t) = -I_L(t-2\Delta t) - \frac{2}{R_L}[u_L(t-\Delta t) - u_L(t-\Delta t)]$$

where $\Delta t$ represents the calculation step of the iteration.

After obtaining the initial values of voltage and current of the AC filter at the time of the fault, the discharge current of the AC filter can be obtained by equation (3).

### 3.2. Principle of waveform similarity

Waveform similarity is an index that characterizes the degree of correlation between waveforms, and the calculation method is shown as follows:

$$\mu(x, y) = \frac{\int_{t_1}^{t_2} x(\tau)y(\tau)d\tau}{\sqrt{\int_{t_1}^{t_2} [x(\tau)]^2 d\tau} \sqrt{\int_{t_1}^{t_2} [y(\tau)]^2 d\tau}}$$

where $\mu(x, y)$ represents the cosine similarity of the waveform, $x(\tau)$ and $y(\tau)$ represent two time-domain waveforms respectively, $t$ represents the starting time of the time window, $T$ represents the length of the time window.

Waveform similarity is a value between [-1, 1]. The closer its value is to 1, the higher the similarity of the two time-domain waveforms. The closer to -1, the lower the similarity of the two waveforms [7]. Therefore, the direction of the fault can be judged by comparing the waveform similarity of the AC line current and the discharge current of the AC filter.

### 3.3. Protection criterion

For the discretization of equation (9), there is
\[ \mu(x, y) = \frac{\sum_{i=1}^{N} x(i) y(i)}{\sqrt{\sum_{i=1}^{N} x^2(i)} \sqrt{\sum_{i=1}^{N} y^2(i)}} \]  

(10)

where \( N \) represents the length of the time window.

The current of the AC line uses the actual measured line current, and the discharge current of the AC filter is calculated according to the aforementioned method. According to the foregoing analysis, the protection criterion based on the characteristics of the AC filter is as follows:

\[ \mu(i_m, i_{fc}) \geq \mu_{set} \]  

(11)

where \( \mu(i_m, i_{fc}) \) represents the waveform similarity between the AC line current and the calculated AC filter discharge current, \( \mu_{set} \) represents the action threshold of the criterion. Considering the reliability and sensitivity of the protection, set it to 0.2.

### 4. Simulation Analysis

In order to verify the correctness of the proposed directional protection criterion, the AC/DC hybrid system shown in Figure 1 was built on the PSCAD/EMTDC platform. The forward fault point is set near the protection installation of the AC line \( (F_1) \), the reverse fault point is set on the converter bus \( (F_2) \). The length of the waveform similarity time window is 1ms, and the phase A metallic ground fault is set at different times. The sampling rate is set to 20kHz, and the protection criterion is judged from 1ms after the fault time.

The simulation result is shown in Figure 5. It can be seen that in the event of a phase A metallic grounding fault, the proposed criteria can accurately determine the direction of the fault within 1.2ms after the fault, and will not malfunction or refusal.

![Wave Simularity vs Time](image)

(a) 0.704s (b) 0.706s (c) 0.714s (d) 0.716s

Fig. 5 Simulation results when phase A metallic ground fault occurs at different times

Table 1 shows the simulation results of other types of metallic faults in the forward and reverse directions at different times. It can be seen from the simulation results that the proposed directional
The protection criterion can accurately determine the direction of the fault within 2ms under different fault types and different fault time. It shows that the proposed directional protection criterion is fast and reliable, and has good characteristics.

Table 1 Simulation results when different types and different directions of faults occur at different time

| Fault Type | Fault Time (s) | Action Time (ms) |
|------------|---------------|------------------|
| F1         | 0.704         | 1.6              | NO              |
|            | 0.706         | 1.2              | NO              |
|            | 0.714         | 1.7              | NO              |
|            | 0.716         | 1.2              | NO              |
| F2         | 0.704         | 1.5              | NO              |
|            | 0.706         | 1.2              | NO              |
|            | 0.714         | 1.5              | NO              |
|            | 0.716         | 1.3              | NO              |

5. Conclusion
The problem of fault direction detection when an outgoing line fault occurs on the AC transmission line in the vicinity of the inverter station is addressed. A novel directional protection scheme based on characteristics of the AC filter is proposed in this paper. When the fault occurs on the DC side outlet of AC lines, there is a great difference of fault current components between forward and reverse fault, due to the discharge process of AC Filter. Moreover, the current provided by AC Filter can be calculated with the measurement of AC line relay and the method is given. Based on that, fault direction can be determined by waveform similarity compare between the current measured by AC line relay and provided by AC filter, since the correlation of these two currents is much higher when a forward fault occurs. The reliability and rapidity of this scheme is verified with comprehensive simulation test.

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