A New Principle of HVDC Protection Based on Two-terminal Electrical Quantities

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Abstract: This paper proposes a new principle of HVDC protection on two-terminal electrical quantities. Based on the analysis of short-circuit faults on different locations, it is found that as for current and voltage variation, there is a large difference between internal and external faults. According to this, the product of rectifier and inverter DC current variation can be used to distinguish the internal and external faults except for opposite pole line faults. In order to distinguish which DC line occurs short-circuit faults, bringing in rectifier and inverter DC voltage variation can achieve the target. This method identifies fault types quickly and has great tolerance of transition resistance. By building a HVDC model on PSCAD/EMTDC, the applicability of faults on different locations can be tested. The simulation result proves that the method has high reliability and can be applied to the whole line.

1. Introduction

Compared with AC transmission, DC transmission has an advantage over high capacity, long distance and asynchronous networking. Nowadays, Chinese HVDC transmission technology develops rapidly: China has already constructed 29 HVDC projects and put them into operation, including 7 UHVDC projects with ±800 kV. These projects transmit energy from west regions to eastern load centers, which can effectively solve the problems of exploitation, transmission and consumption of hydropower, wind power, photovoltaic energy, producing remarkable economic and social profits. At present, ABB’s and SIEMENS’s traveling wave protection schemes are applied widely for HVDC lines. Based on the catadioptric principle of traveling wave, these two schemes take traveling wave protection as main protection and take differential undervoltage protection and longitudinal differential protection as backup protections. The main criteria of traveling wave protection are DC voltage variation $\Delta U$, DC voltage variation rate $dU/dt$ and DC current variation $\Delta I$. However, transition resistance has great influences on these criteria [1–4]. On condition that there is a large transition resistance in the DC system, relay protection device may reject action which will decrease reliability of the system. When DC line short-circuit fault occurs, DC current and voltage with plenty of fault information can be measured at the outlet of the rectifier and inverter. Therefore, DC current and voltage variation can be analyzed on different fault conditions [5–8]. This paper uses the product’s positive and negative characteristics of DC current variation $\Delta I_+\pi$ and $\Delta I_-$ on both sides as well as DC voltage variation $\Delta U_+\pi$ and $\Delta U_-$ to distinguish internal and external faults. The simulation results show that the method can distinguish internal and external faults quickly and initiate protection device.
with internal faults. Besides, the method has great tolerance of transition resistance and can be applied widely.

2. DC current and voltage variation analysis with different locations’s fault

As is shown in figure 1, bipolar HVDC transmission system includes rectifier(R side), inverter(I side), smoothing reactor, DC filter and DC transmission lines. $u_{R_p}$ and $u_{R_n}$ respectively represent rectifier side positive and negative pole voltage; $i_{R_p}$ and $i_{R_n}$ respectively represent rectifier side positive and negative pole current; $u_{I_p}$ and $u_{I_n}$ respectively represent inverter side positive and negative pole voltage and $i_{I_p}$ and $i_{I_n}$ respectively represent inverter side positive and negative pole current. The paper regulates that the positive direction of the current is from R side to I side.

![Bipolar HVDC system](image)

**Figure 1.** Bipolar HVDC system

Figure 2 shows that in the bipolar HVDC transmission system there are several locations that may occur short-circuit faults, including $d_1$, $d_2$, $d_3$ and $d_4$. Among these locations, $d_1$ represents internal fault and others represent external faults.

![Faults on different locations in bipolar HVDC system](image)

**Figure 2.** Faults on different locations in bipolar HVDC system

The paper aims to ensure that the protection device can correctly distinguish internal and external faults and protection wouldn’t reject act with a large transition resistance. According to the analysis of DC current and voltage from rectifier and inverter side, the corresponding method can be proposed to distinguish different types of faults.
2.1. Electrical variations with internal faults
When DC line short-circuit fault occurs, it equals to add a reverse power $U_f$ which has the same amplitude and opposite polarity compared with fault voltage according to the principle of superposition. As can be seen in figure 3, $L_d$ represents smoothing reactor; $Z_R$ and $Z_I$ respectively represent the line equivalent impedance of the rectifier and inverter side, separated by the short circuit point and $Z_F$ represents the equivalent impedance of the DC filter.

![Figure 3. Equivalent circuit of internal fault](image)

When $f$ point occurs a short-circuit fault, reverse power $U_f$ injects short-circuit current to rectifier and inverter side, respectively. The direction of short-circuit current rejecting to rectifier side is from rectifier to inverter side, so the rectifier DC current variation $\Delta I_R = I_R^{(1)} - I_R^{(0)} > 0$. However, the direction of short-circuit current rejecting to inverter side is from inverter to rectifier side, which means the inverter DC current variation $\Delta I_I = I_I^{(1)} - I_I^{(0)} < 0$. In addition, DC voltage variations from both sides decline sharply.

It can be inferred that:

$$\begin{align*}
\Delta I_R &> 0 & \Delta I_I &< 0 \\
\Delta U_R &< 0 & \Delta U_I &< 0 
\end{align*}$$

We can easily deduce that:

$$\Delta I_R \cdot \Delta I_I < 0$$

The interpole fault is the most serious fault belonging to internal faults which has the same changing direction of DC current and voltage as monopole faults. The only difference is that the variation of DC current and voltage is larger.

2.2. Electrical variations with external faults

2.2.1. Grounding short-circuit fault on the outlet of the rectifier. Figure 4 shows an equivalent circuit of grounding short-circuit fault on the outlet of the rectifier. $Z_L$ represents the equivalent impedance of the DC transmission line.

![Figure 4. Equivalent circuit of grounding short-circuit fault on the outlet of the rectifier](image)
When f point occurs short-circuit fault, reverse power $U_f$ injects short-circuit current to rectifier and inverter side, respectively. The direction of short-circuit current rejecting to both sides is from inverter to rectifier side, so the rectifier DC current variation $\Delta I_R = I_R^{(1)} - I_R^{(0)} < 0$ and the inverter DC current variation $\Delta I_I = I_I^{(1)} - I_I^{(0)} < 0$.

It can be inferred that:

$$\begin{align*}
\Delta I_R &< 0 \\
\Delta I_I &< 0
\end{align*}$$

We can easily deduce that:

$$\Delta I_R \cdot \Delta I_I > 0$$

2.2.2. **Grounding short-circuit fault on the outlet of the inverter.** Figure 5 shows an equivalent circuit of grounding short-circuit fault on the outlet of the inverter.

![Figure 5](image)

**Figure 5.** Equivalent circuit of grounding short-circuit fault on the outlet of the inverter

When f point occurs short-circuit fault, reverse power $U_f$ injects short-circuit current to rectifier and inverter side, respectively. The direction of short-circuit current rejecting to both sides is from rectifier to inverter side, so the rectifier DC current variation $\Delta I_R = I_R^{(1)} - I_R^{(0)} > 0$ and the inverter DC current variation $\Delta I_I = I_I^{(1)} - I_I^{(0)} > 0$.

It can be inferred that:

$$\begin{align*}
\Delta I_R &> 0 \\
\Delta I_I &> 0
\end{align*}$$

We can easily deduce that:

$$\Delta I_R \cdot \Delta I_I > 0$$

2.2.3. **Grounding short-circuit fault on the opposite line.**

Figure 6 illustrates that the only difference between grounding short-circuit fault on the opposite line and internal fault is the direction of the reverse power.

![Figure 6](image)

**Figure 6.** Equivalent circuit of grounding short-circuit fault on the opposite line
When f point occurs short-circuit fault, reverse power $U_f$ injects short-circuit current to rectifier and inverter side on the opposite line, respectively. The direction of short-circuit current rejecting to the rectifier side is from inverter to rectifier side. When the current reaches DC bus on the rectifier side, part of the short-circuit current will flow from DC bus to the inverter side, so the rectifier DC current variation $\Delta I_R = I_R^{(1)} - I_R^{(0)} > 0$. On the contrary, the direction of short-circuit current rejecting to inverter side on the opposite line is from the rectifier to inverter side, and as soon as the short-circuit current reaches the DC bus on the inverter side, part of it will flow from DC bus to the rectifier side, which means the inverter DC current variation $\Delta I_I = I_I^{(1)} - I_I^{(0)} < 0$. Besides, DC voltage variations on both sides change slightly.

It can be inferred that:

$$\begin{cases} \Delta I_R > 0 \\ \Delta I_I < 0 \end{cases}$$

We can easily deduce that:

$$\Delta I_R \cdot \Delta I_I < 0$$

3. Protection principle

3.1. Protection setting process

Figure 7 displays the flow chart of HVDC protection based on two-terminal electrical quantities.

![Flow chart of HVDC protection based on two-terminal electrical quantities](image_url)

3.2. Protection setting calculation

When it comes to calculate the value of the DC voltage variation $|\Delta U_R \cdot \Delta U_I|$, avoiding the maximum value of the fault on the opposite DC line should be considered and calculated as equation (1). The corresponding sensitivity check can be calculated as equation (2).

$$\begin{align*}
|\Delta U_R \cdot \Delta U_I|_{set} &= K_{rel} \cdot |\Delta U_R \cdot \Delta U_I|_{out} \\
K_{sen} &= \frac{|\Delta U_R \cdot \Delta U_I|_{min}}{|\Delta U_R \cdot \Delta U_I|_{set}}
\end{align*}$$
where $|\Delta U_R \cdot \Delta U_I|_{set}$ represents the protection set value of DC voltage variation, $|\Delta U_R \cdot \Delta U_I|_{min}$ represents the minimum value of internal faults, and $K_{rel}$ represents confidence coefficient.

4. Simulation analysis

4.1. Simulation of protection principle

By means of PSCAD/EMTDC, we can get diagrams of DC current and voltage on both sides. Suppose that the grounding short-circuit fault occurs on the middle of the DC transmission line: the fault occurs at 0.5s, fault duration is 0.1s and the simulation time is 2s. Figure 8 shows DC current and voltage with internal faults; Figure 9 shows DC current with grounding short-circuit fault on the outlet of the rectifier; Figure 10 shows DC current with grounding short-circuit fault on the outlet of the inverter; Figure 11 shows DC current and voltage with grounding short-circuit fault on the opposite DC line.

![Figure 8(a). Rectifier DC current and voltage](image)

![Figure 8(b). Inverter DC current and voltage](image)

![Figure 9. Rectifier and inverter DC current](image)
The above-mentioned information will be gathered in table 1.

**Table 1.** Variation of two-terminal electrical quantities in different fault situations

| Fault type                     | $\Delta I_R$ | $\Delta I_I$ | $\Delta I_R \cdot \Delta I_I$ | $|\Delta U_R \cdot \Delta U_I|$ |
|-------------------------------|--------------|--------------|-------------------------------|-------------------------------|
| Internal fault                | $>0$         | $<0$         | $<0$                          | Larger                        |
| Grounding short-circuit fault | $<0$         | $<0$         | $>0$                          | \                            |
| on the outlet of the rectifier|              |              |                               |                               |
| Grounding short-circuit fault | $>0$         | $>0$         | $>0$                          | \                            |
| on the outlet of the inverter |              |              |                               |                               |
Grounding short-circuit fault on the opposite line

|   | >0 | <0 | <0 | Smaller |
|---|----|----|----|---------|

Based on the analysis, we can get the information that when external faults except for grounding short-circuit fault on the opposite line occur, the relay protection device can distinguish internal and external faults through the positive and negative characteristics of $\Delta I_R \cdot \Delta I_I$. And the transition resistance won’t influence the process of judgement. However, when grounding short-circuit fault on the opposite line occurs or there exists external disturbance in the system, judging the positive and negative characteristics of $\Delta I_R \cdot \Delta I_I$ cannot distinguish internal and external faults. The simulation results illustrate that compared with internal faults, DC voltage variations on both sides are much smaller. Therefore, the value of $|\Delta U_R \cdot \Delta U_I|$ can be used to choose the fault line. As for it, the greatest advantage is that protection device can correctly operate even though there is a large transition resistance on the fault point or external disturbance affects the system.

### 4.2. Protection sensitivity check

By means of PSCAD/EMTDC, we can build bipolar HVDC transmission system of ±500 kV with rated transmission power of 1000MW and 500-kilometer-long line. Fault points will be set in the middle of positive and negative line, respectively. In the process of simulation, sampling frequency is 10kHz. In addition, the example requires that $K_{rel} = 1.2$ and the set value of $|\Delta U_R \cdot \Delta U_I|$ should meet the demand that $K_{sen-min} = 2.5$. According to the simulation results, when the grounding short-circuit occurs on the inverter side of the opposite line, the measured value of $|\Delta U_R \cdot \Delta U_I|$ reaches its maximum. Since it takes some time for traveling wave to reach the middle of the line, protection device will operate in 1.5 ms. The values of $|\Delta U_R \cdot \Delta U_I|$ with internal and external faults are shown as table 2.

| Fault location | Internal fault ($d_1$) | External fault ($d_2$) |
|----------------|------------------------|------------------------|
| $|\Delta U_R \cdot \Delta U_I|$ (p.u.) | 1.7191 | 0.0987 |

With equation (1) and (2), we can get:

$|\Delta U_R \cdot \Delta U_I|_{set} = K_{rel} \cdot |\Delta U_R \cdot \Delta U_I|_{out} = 1.2 \times 0.0987 = 0.1184$

$K_{sen} = \frac{|\Delta U_R \cdot \Delta U_I|_{min}}{|\Delta U_R \cdot \Delta U_I|_{set}} = \frac{1.7191}{0.1184} = 14.5$

### 4.3. The effects of transition resistance

When external faults except for grounding short-circuit fault on the opposite line occur, the protection device can distinguish internal and external faults through the positive and negative characteristics of $\Delta I_R \cdot \Delta I_I$. And the transition resistance won’t influence the process of judgement. Even if there exists external disturbance in the system, measuring whether the value of $|\Delta U_R \cdot \Delta U_I|$ is larger than set value can filter the disturbance and it also can judge which line occurs short-circuit faults. In this process, transition resistance will slightly influence the protection. On this condition, the measured DC voltage variation with grounding short-circuit fault on the opposite line is much smaller than internal
faults. Thus, the protection can act correctly. The protection actions of internal and external faults under different transition resistances are shown in table 3.

| Fault point | Transition resistance(Ω) | |  \( \Delta U_R \cdot \Delta U_I \) | Judging results |
|-------------|--------------------------|---|----------------|----------------|
| \( d_1 \)   | 0.1                      |   |  2.39         | Internal fault |
|             | 100                      |   |  1.0878       | Internal fault |
|             | 800                      |   |  0.1628       | Internal fault |
| \( d_2 \)   | 0.1                      |   |  0.0255       | External fault |
|             | 100                      |   |  0.0165       | External fault |
|             | 800                      |   |  0.0066       | External fault |

4.4. The effects of control system
In general, the control system works in 5–6ms after a fault occurs. By analyzing the simulation results, we know that the protection device may have mistaken actions in a period of time when the control system begins to work until current and voltage reach to their rated value. In this case, the protection scheme can be the main protection for 5–6ms after the protection device begins to operate. Then the protection will be out of service 5–6ms later and backup protections containing differential undervoltage protection and longitudinal differential protection will work as main protections until DC current and voltage reach to their rated value.

4.5. The effects of fault locations
It is likely that the protection actions may be affected by fault locations. Therefore, it is necessary to analyze the effects of fault locations. Table 4 displays protection actions of internal and external faults under different locations.

| Fault point | Distance of fault point to rectifier side(km) | |  \( \Delta U_R \cdot \Delta U_I \) | Judging results |
|-------------|---------------------------------------------|---|----------------|----------------|
| \( d_1 \)   | 10                                         |   |  1.8340        | Internal fault |
|             | 250                                        |   |  2.39          | Internal fault |
|             | 490                                        |   |  1.7191        | Internal fault |
| \( d_2 \)   | 10                                         |   |  0.0536        | External fault |
|             | 250                                        |   |  0.0255        | External fault |
|             | 490                                        |   |  0.0987        | External fault |

5. Conclusion
This paper proposes a new principle of HVDC protection based on two-terminal electrical quantities. By judging the positive and negative characteristics of \( \Delta I_R \cdot \Delta I_I \), we can distinguish internal and external faults except for grounding short-circuit fault on the opposite line. However, as grounding
short-circuit fault on the opposite line occurs, we can use the value of \( |\Delta U_R \cdot \Delta U_I| \) to choose the fault line. Above all, the scheme is still available with a large transition resistance. Compared with widely applied DC protections, the scheme only makes use of two-terminal currents and voltages and the protection acts quickly. Besides, it has strong anti-interference ability with high reliability.

6. References

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