Dynamic behavior analysis of backup protection for HVDC transmission line

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Abstract. The backup protection of HVDC transmission line consists of differential undervoltage protection and differential protection. In this paper, based on the actual parameters, the simulation model of differential undervoltage protection and differential protection for DC line is built. The response regularity of each criterion of the two protections under different fault conditions is studied. The basic functions of each criterion are defined, which provides an important basis for the setting calculation of DC line backup protection.

1. Introduction
DC line plays an important role in HVDC transmission system [1-4]. Differential undervoltage protection and differential protection are mainly used as backup protection for existing DC transmission lines, which cooperate with traveling wave protection (the main protection of DC line) to form a complete DC transmission line protection system, so as to further improve the reliability of DC line operation [5-7].

At present, the protection setting of traditional AC system has formed a relatively complete calculation method. Compared with it, it is difficult to study the dynamic transmission characteristics of DC line under fault condition by analytical method. Especially, as the backup protection of DC line, the change of electrical quantity is significantly affected by DC control, so the setting calculation of DC line backup protection has been lack of systematic and effective methods. The function of each criterion, the basis of parameter calculation and the factors affecting the performance of protection are not fully understood [8-11]. In order to ensure the reliability of DC line protection, it is necessary to analyze the dynamic behavior of DC line backup protection.

In this paper, PSCAD / EMTDC electromagnetic transient simulation model for differential undervoltage protection and differential protection of DC line is established. The dynamic behavior of each protection criterion in the two protections under different fault conditions is analyzed, and the function of each criterion is also studied. The research results of this paper not only help to understand the function of the two protections, but also provide the basis for the setting of the protection, which has important theoretical and practical value.

2. Protection range and related fault types of DC line backup protection
Differential undervoltage protection and differential protection are equipped on the rectifier side of the positive and the negative line in HVDC system, and the protection range is also the full length of the positive or the negative line.
Taking the DC line backup protection on the positive line as an example, and various faults and their distribution that need to be considered in the analysis of protection action behavior are shown in Figure 1:

![Figure 1. Fault distribution diagram](image)

**Figure 1. Fault distribution diagram**

See Table 1 for specific description of the fault:

**Table 1. Fault type**

| Range            | NO.  | Fault description                                      |
|------------------|------|--------------------------------------------------------|
| Internal fault   | d₁   | Earth fault on the positive line                       |
| External fault   | d₂   | Earth fault on the negative line                       |
| External fault   | d₃   | Earth fault at the valve side of the smoothing reactor, rectifier side, positive line |
| External fault   | d₄   | Earth fault at the valve side of the smoothing reactor, inverter side, positive line |
| External fault   | d₅   | Three phase short circuit fault of AC bus at rectifier side |
| External fault   | d₆   | Three phase short circuit fault of AC bus at inverter side |

The parameters of the actual HVDC system used in the study are as follows: the rated voltage is 500kV, the rated current is 1.8kA, the bipolar rated transmission power is 1800MW, and the length of the DC transmission line is 960km.

### 3. DC line backup protections and the dynamic behavior analysis

#### 3.1. DC line differential undervoltage protection and its dynamic behavior analysis

**3.1.1. Operation equation of differential undervoltage protection.** The operation equation of DC line differential undervoltage protection is

\[
\begin{align*}
\left\{ \frac{du}{dt} &> k₁ \\
|μ_{al}| &< k₂
\end{align*}
\]

(1)

It can be seen from formula (1) that the protection mainly consists of two criteria: one is the voltage change rate du/dt, and the other is the low voltage criterion (the absolute value of the DC line voltage). The criterion du/dt is the same as that in the traveling wave protection, such as the principle, calculation method and setting value, etc., which can be seen in reference [12]. In addition, as a backup protection, the differential undervoltage protection also has protection delay.
After the differential undervoltage protection acts, DC line fault recovery sequence (DFRs) will be started. If the number of recovery exceeds the preset number, the pole will be locked [4].

3.1.2. Dynamic behavior of $\frac{du}{dt}$. In the differential undervoltage protection, the voltage change rate $\frac{du}{dt}$ is the same as that in traveling wave protection of DC line. Therefore, the analysis of its action behavior can refer to the published literature [12], and only the relevant conclusions are given in this paper: the response of $\frac{du}{dt}$ to the faults at $d_1$ and $d_2$ is significantly greater than that to the faults at $d_3$, $d_4$, $d_5$ and $d_6$.

3.1.3. Dynamic behavior of $|u_{dl}|$. The dynamic response of $|u_{dl}|$ under different types of fault conditions is shown in Figure 2:

![Figure 2(a)](image1.png)  
(a) Dynamic behavior of $|u_{dl}|$ for positive and negative line fault  

![Figure 2(b)](image2.png)  
(b) Dynamic behavior of $|u_{dl}|$ for other external faults

Figure 2. Response of $|u_{dl}|$ with different faults

Figure 2(a) shows the response of $|u_{dl}|$ when there is a fault occurs at the positive line ($d_1$) and the negative line ($d_2$) respectively. When a fault occurs on the positive line, $|u_{dl}|$ of the positive line drops sharply and maintain at a very low voltage level. At the beginning of the fault, the voltage fluctuation is greater, but in the following period, the voltage fluctuation is smaller. When the negative line fails, $|u_{dl}|$ of the positive line also fluctuates, but compared with the drop of it when the positive line fails, it has a smaller drop, and the voltage can gradually return to the normal level under control system. Compare the two curves in Figure 2(a), the Change trend of $|u_{dl}|$ is quite different when fault occurs at $d_1$ and $d_2$.  

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Figure 2(b) shows the response of \( |\mu_{dl}| \) on the positive line when fault occurs at d3 to d6. Compared with Figure 2(a), the dynamic response of \( |\mu_{dl}| \) is very close to the dynamic response of it when fault occurs at d2.

3.1.4. Function analysis of differential undervoltage protection. The voltage change rate \( \frac{du}{dt} \) can distinguish the faults at d1 and d2 from those at d3 to d6 reliably. Therefore, the main function of the voltage change rate \( \frac{du}{dt} \) is to determine whether the fault occurs on the transmission line [12].

The low voltage criterion \( \mu_{dl} \) can distinguish the fault at d1 from that at d2. Therefore, the main function of the low voltage criterion \( \mu_{dl} \) is to determine whether the fault occurs on the positive line or the negative line, that is, it has the function of fault line selection.

3.2. DC line differential protection and its dynamic behavior analysis

The DC line differential protection is mainly used to detect the high resistance ground fault. The operation equation of the DC line differential protection is

\[
|\int_{i_{dl}} - i_{dl_{os}}| > k
\]  

(2)

Where \( i_{dl} \) and \( i_{dl_{os}} \) are the current measured at the rectifier side and the converter side respectively. At the same time, as the backup protection of DC line traveling wave protection and differential undervoltage protection, the DC line differential protection has protection delay to cooperate with other protections.

The dynamic response of \( |\int_{i_{dl}} - i_{dl_{os}}| \) when high resistance ground fault occurs at different position is shown in Figure 3:

![Graph showing the dynamic response of \( |\int_{i_{dl}} - i_{dl_{os}}| \) for positive and negative line fault](attachment:graph1.png)

(a) Dynamic behavior of \( |\int_{i_{dl}} - i_{dl_{os}}| \) for positive and negative line fault

![Graph showing the dynamic response of \( |\int_{i_{dl}} - i_{dl_{os}}| \) for other external faults](attachment:graph2.png)

(b) Dynamic behavior of \( |\int_{i_{dl}} - i_{dl_{os}}| \) for other external faults

**Figure 3.** Response of \( |\int_{i_{dl}} - i_{dl_{os}}| \) with different faults
It can be seen from Figure 3(a) that when the positive line has a ground fault, \( \left| \frac{d}{dt} i_{di} - i_{di,os} \right| \) maintains at a certain level after a period of fluctuation, while when the negative line has a fault, the value of it is always small.

Figure 3(b) shows the dynamic response of \( \left| \frac{d}{dt} i_{di} - i_{di,os} \right| \) when fault occurs at d3 to d6. And it can be seen that the dynamic response of \( \left| \frac{d}{dt} i_{di} - i_{di,os} \right| \) is very close to that when fault occurs at d2.

Therefore, criterion \( \left| \frac{d}{dt} i_{di} - i_{di,os} \right| \) can directly distinguish whether the fault occurs on the positive line or the negative line.

4. Conclusions
In the DC line differential undervoltage protection, the main function of the voltage change rate \( \frac{du}{dt} \) is to determine whether the fault occurs on the transmission line.

The main function of the low voltage criterion \( |u_{dl}| \) in the DC line differential undervoltage protection is to determine whether the fault occurs on the positive line or the negative line.

In the DC line differential protection, the criterion \( \left| \frac{d}{dt} i_{di} - i_{di,os} \right| \) can not only distinguish whether the fault occurs on the line, but also distinguish whether the fault occurs on the positive or the negative line.

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