Research On Intelligent Reclosing Cooperated By Combined Fault Location Method

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Abstract. With the rapid development of UHV DC transmission, there is an increasing demand for the construction of AC/DC hybrid systems. Because the AC/DC hybrid system requires high system stability on the AC side, an intelligent reclosing strategy is needed to ensure that the line will not reclose after a permanent fault occurs. Based on the traditional voltage criterion, this paper has proposed a new discriminant that can stably distinguish the fault type to reduce the error judgment range, maintain the stability of the power system and ensure the safe and continuous operation. This paper also did a simulate with the RTDS (Real-time Simulation System) to verify the accuracy and reliability of the new discriminant.

1. Introduction

UHVDC transmission system has high voltage level, and can be applied in power system with asynchronous interconnection. At present, the construction and operation of the AC / DC hybrid system have become a trend. However, a simple fault of a single AC system may also cause commutation failure of converter station and cause DC blocking. Once the DC blocking fault occurs, there will be a huge power shortage in the receiving power grid, which may influence the frequency and voltage stability of the system.

In the AC side of EHV transmission lines, the operation experience shows that the instantaneous fault is the most common. Therefore, single reclosing technology is widely used in EHV transmission lines to eliminate transient faults and restore transmission quickly. However, the traditional automatic reclosing technology does not distinguish permanent fault from instantaneous fault, and there is no reasonable logic in reclosing strategy, which is easy to cause some adverse effects on the electrical system. For the permanent fault of the UHVDC converter station near the AC transmission line, the secondary impact of reclosing on the converter station caused by the permanent fault is very easy to cause continuous commutation failure and even the malignant accident of bipolar locking in the converter station. Therefore, the method to distinguish the fault type is significant. If it is identified as a transient fault, reclosing can be carried out after arc extinction. For permanent fault, reclosing should be lockout to maintain the stability of the system.

In recent years, the theory of fault type identification has been developed continuously. Reference [1] proposed to use the capacitive coupling voltage of the EHV transmission line to distinguish instantaneous fault from permanent fault and to reclose instantaneous fault and not to reclose permanent fault. The disadvantage of this method is that it is easy to misjudge when the mutual inductance voltage in the line is greater than the capacitance coupling voltage. In reference [2], the
fuzzy synthesis strategy was used to optimize the voltage criterion, which reduced the misjudgment rate, but there was still a 7% false judgment area, which was determined by the defects of the fuzzy theory itself. Reference [3-5] process the digital signal of the fault to distinguish the fault type. However, the arc model is controversial, and it is difficult to determine an accurate model, which limits the universality of this method.

Intelligent reclosing refers to the use of intelligent and reasonable reclosing logic for reclosing based on identifying fault types and judging whether reclosing is needed, to maintain the safety and stability of lines and protect the equipment of the power system. To realize intelligent reclosing, it is necessary to distinguish permanent or instantaneous faults. Firstly, this paper analyses the disadvantages of the existing permanent fault identification algorithm based on voltage characteristics. Secondly, this paper proposes an improved algorithm based on fault location algorithm. Lastly, simulations in RTDS (Real-time Digital Simulation System) are established to verify the feasibility of the new algorithm.

2. Permanent fault recognition algorithm based on voltage characteristics

2.1. Capacitance coupling voltage

After a permanent fault, the capacitive coupling voltage at the fault will rapidly decay, so the value of transition resistance determines the voltage at the fault point. The fault model is shown in Figure 1.

\[ \dot{U}_f = U_{fr} \]  

Figure 1. Fault on phase C.

When the fault type is a metallic fault,

\[ U_f = 0 \]  

In the transient fault, because the fault point disappears after arc extinction, there is capacitance coupling voltage

\[ \dot{U}_f = \dot{U}_y = \frac{b_1-b_0}{2b_1+b_0}(\dot{U}_a + \dot{U}_b) \]  

In the above formula, \( \dot{U}_y \) is the capacitance coupling voltage at the fault point; \( b_1 \) and \( b_0 \) are positive and zero sequence susceptance per unit length; \( \dot{U}_a \) and \( \dot{U}_b \) is the voltage of the other two phases at the fault.

When an outlet fault, a terminal fault and a middle fault occur in a transmission line through the simulation in RTDS. As the transition resistance increases, the voltage at the fault point keeps increasing and approaching a constant gradually, the value of this constant is the capacitance coupling voltage. Therefore, it can be understood that the fault voltage of a transient fault is equivalent to the fault voltage of a permanent one which has infinite transition resistance.
2.2 Inductive coupling voltage

\[ U_{\text{XL}} = (I_a + I_b)Z_m L = \frac{(I_a+I_b)(Z_o-Z_1)L}{3} = U_X L \]  

(4)

In the above formula, \( U_{\text{XL}} \) is the inductively coupled voltage; \( I_a \) and \( I_b \) is the current of two sound phases; \( Z_m \) is the mutual inductance of unit length line, \( L \) is the length of the line, \( Z_o \) and \( Z_1 \) are zero sequence and positive sequence impedance per unit length of line respectively, \( U_X \) is the inductive coupling voltage per unit length of the line.

Therefore, it can be seen that inductive coupling voltage exists in both permanent and transient faults, and the inductive coupling voltage from the fault to the protection installation location is directly proportional to the distance between them.

2.3 traditional voltage criterion

The traditional voltage criterion generally compares the voltage on the fault phase

\[ U_m \geq K_K U_{\text{XL}} \quad K_K = 1.1-1.2 \]  

(5)

When the fault type is an instantaneous fault, the measured point voltage is the sum of \( U_{\text{XL}} \) plus \( U_y \), which is greater than the inductive coupling voltage multiplied by a coefficient. In a permanent fault, the capacitance coupling voltage rapidly decays, the measurement point only has inductive coupling voltage, which is less than the determined value, in this case, the criterion identifies it as a permanent fault. However, the traditional voltage criterion will cause misjudgement when the capacitive coupling voltage is small, because the inductive coupling voltage of the protection device at the measuring point is less than the inductive coupling voltage of the entire line.

For example, we assume the voltage value read at both sides:

\[ U_{am} = kU_{xl}, \quad U_{an} = (1-k)U_{xl} \]  

(6)

When \( k = 1/2 \), that is, the midpoint of the line. Set up \( \frac{U_{cc}}{U_{xl}} = m \),

\[ |U_{am}| = |U_{an}| = \sqrt{m^2 + \frac{1}{4}} U_{xl} \]  

(7)

If we take the coefficient \( K_K = 1.1 \), when \( m < \frac{4\sqrt{6}}{10} \), \( |U_{am}| = |U_{an}| < 1.1U_{xl} \). At this time, the instantaneous fault that occurred in the middle point of the line may be misjudged as a permanent fault.

3. A new algorithm for permanent fault identification

If the coefficient \( K_K \) is reduced, it can reduce the range of misjudgment, but the essence problem of misjudgement is not solved. Therefore, the identification method can be improved by cooperating with fault location method. After the fault location is completed, the capacitance and inductive coupling voltage are calculated and compared with the measured voltage. In this way, the influence of the ratio
of capacitance and inductive coupling voltage on the result of the criterion can be avoided, and the range of misjudgment area can be effectively reduced.

### 3.1. fault location mode

The new algorithm of permanent fault identification proposed in this paper has relatively high requirements for the accuracy of fault location results, so the combination of impedance and traveling wave fault location method is adopted.

It is mainly divided into the following steps:

1. **The approximate distance of the fault point was estimated by the impedance method**

   
   \[ X_r = \frac{X_m - \frac{R_m \tan \phi - X_m}{\tan \phi \cot (\arg \left( \frac{I_f}{I_m} \right))}}{X_i} \]  
   
   \[ (8) \]

   In the above formula, \( X_r \) is the fault distance that is determined preliminarily; \( X_i \) is the positive sequence reactance per unit length; \( R_m \) and \( X_m \) are the resistance reactance at the installation site, they are obtained from the ratio of voltage and current at the measuring point, \( \frac{U_m}{I_m} = R_m + jX_m \); \( \phi \) is the positive sequence impedance angle; \( I_f \) is the fault component current.

2. **Estimated fault point distance interval:**

   A large number of simulations show that the positioning error of the measurement impedance method is within 10%[6], so the actual distance of the fault point will be in the interval \( (X_r - 10\%L, X_r + 10\%L) \), \( L \) is the length of the line.

3. **The traveling wave signal is read and the wavelet transform is carried out to obtain the maximum value of multiple groups of modulus**

   After the fault occurs, the fault point will produce a transient traveling wave which propagates to both ends. The wave head that first arrives at the protection installation end is the initial traveling wave time of fault \( t_0 \). The arrival time of the traveling wave reflected from the fault point is \( t_1 \). The arrival time of the reflected traveling wave from the opposite side is \( t_2 \). They satisfy the following requirements:

   \[ \begin{align*}
   v(t_1 - t_0) &= 2x \\
   v(t_2 - t_0) &= 2(L - x)
   \end{align*} \]  
   
   \[ (9) \]

   \( x \) is the distance of fault point.

   After the fault occurs, the transient traveling wave has mutation and singularity, the traditional Fourier transform cannot reflect the characteristics of the average in a specific period, while wavelet analysis can localize the time and frequency domain and detect the mutation point.

   set up \( W_{\psi f}(s,x) \), \( f(t) \) is a signal under the set scale, if for any \( x, \ x \in (x_0 - \delta, x_0 + \delta) \), satisfies

   \[ |W_{\psi f}(s,x)| \leq |W_{\psi f}(s,x_0)| \]  
   
   \[ (10) \]

   It is called \( x_0 \) is the modulus maximum point under this scale, \( W_{\psi f}(s,x) \) is the modulus maximum.

   The mutation point of transient traveling wave can correspond to the modulus maximum point of wavelet transform to obtain multiple groups of time \( T_1 \) and \( T_2 \).

4. **Filter out a set of time data closest to the condition**

   Filtered data \( T_1, T_2 \) The following formula should be satisfied:

   1. Firstly, determine

   \[ \begin{align*}
   t_0 + \frac{2X_r}{v} - 2 \times \frac{10\%L}{v} < T_1 < t_0 + \frac{2X_r}{v} + 2 \times \frac{10\%L}{v} \\
   t_0 + \frac{2(L - X_r)}{v} - 2 \times \frac{10\%L}{v} < T_2 < t_0 + \frac{2(L - X_r)}{v} + 2 \times \frac{10\%L}{v}
   \end{align*} \]  
   
   \[ (11) \]

   Discarding the data that is not satisfied.

   2. Then determine

   \[ \Delta T_1 + \Delta T_2 = \frac{2L}{v} \]  
   
   \[ (12) \]
\[ \Delta T_1 \text{, } \Delta T_2 \text{ are the time difference of the initial traveling wave time is subtracted from the time point corresponding to the modulus maximum value, and a group of modular maximum values which are closest to the time corresponding relationship is selected to ensure that they satisfying the condition of equation (9)} \]

(5) A set of time data obtained is brought back to equation (9) to calculate the fault distance \( x_1 \) and \( x_2 \), average the two values \( l = \frac{x_1 + x_2}{2} \), which is returned as the ranging result.

### 3.2. improved judgment method

After the transient fault arc is extinguished, the fault point disappears, and there is a coupling relationship between the healthy phase and the fault phase, which makes the recovery voltage exist on the disconnected phase. The fault point of permanent fault always exists, and its residual voltage characteristic is different from the instantaneous fault. The essence of voltage criterion is to distinguish transient and permanent faults based on the characteristics of recovery voltage after arc extinction.

However, when a fault occurs in a large transmission line whose capacitance coupling voltage is small, it will interfere with the traditional voltage criterion which only sets the parameters related to the inductive coupling voltage, leading to misjudgment. It can only be confirmed that under ideal conditions, when the formula is satisfied, the fault type can be determined as a transient fault, but when the formula is not established, it may be permanent fault or transient fault, that is to say, the traditional criterion cannot ensure that all transient faults can be determined. When the ratio of capacitance coupling voltage and inductive coupling voltage is less than a threshold value related to line parameters and fault location, the transient fault will be misjudged as a permanent fault.

When a permanent fault occurs, because the fault point always exists, whether it is metal grounding or through fault resistance, as long as the fault resistance is a finite value, the voltage at this point must be less than the capacitance coupling voltage when the instantaneous fault occurs. Therefore, the permanent fault judgment can be realized by the following formula:

\[ U_f < U_{y} + U_{X_L} = \frac{b_1 - b_0}{2b_1 + b_0} (U_a + U_b) + (I_a + I_b)Z_m l \]

(13)

\[ U_f \] is the capacitance coupling voltage at the fault point; \( b_1 \) and \( b_0 \) are positive sequence and zero sequence susceptance per unit length; \( I_a \) and \( I_b \) is the current of two sound phases; \( Z_m \) is mutual inductance of unit length line; \( l \) is the fault location result; \( U_a \) and \( U_b \) is the voltage of the other two sound phases at the fault, which can be obtained from equation (14)

\[
\begin{align*}
U_a &= U_{ma} - (I_a Z_l + I_b Z_m) l \\
U_b &= U_{mb} - (I_b Z_l + I_a Z_m) l \\
\end{align*}
\]

(14)

So the standard is put forward

\[ U_{set} = \left[ \frac{b_1 - b_0}{2b_1 + b_0} (U_a + U_b) \right] K_1 + (I_a + I_b)Z_m l K_2 \]

(15)

\( K_1 \) and \( K_2 \) Take 0.8 ~ 0.9, leaving a certain judgment margin, which is determined by different working conditions and judging range requirements. For example, when the capacitance coupling voltage in the line accounts for a large proportion, we can increase \( K_1 \) Value of, decrease \( K_2 \) It can reduce the misjudgment caused by disturbance and error, and make the criterion more reliable.

\[ U_m < U_{set} \]

(16)

When the voltage at the measuring point is less than the fixed value, it is judged as a permanent fault, and reclosing is locked to maintain the stability of the power system; otherwise, it is determined as an instantaneous fault, and reclosing operation is conducted after a delay.

### 4. Simulation results

To verify the correctness of the theoretical analysis, this paper uses RTDS (Real-time Digital Simulation System) to carry out a digital simulation experiment. The experimental system is the receiving end grid of ± 1100kV Changji (Xinjiang) - Guquan (Anhui) UHVDC transmission system.
The AC side system is divided into several sections. The main research part is the line connecting the DC side and the AC side. Among them, the guquan to fanchang line is 58km in length, the M side is guquan, the N side is fanchang, and the M side system positive sequence impedance \( z_{m1} = j26.18\Omega \), zero sequence impedance \( z_{m0} = j24.71\Omega \). N side system positive sequence impedance \( z_{n1} = j56.21\Omega \), zero sequence impedance \( z_{n0} = 27.61\Omega \). The positive sequence parameter of the transmission line \( z_{t1} = j0.43\Omega/km \), \( \omega_{c1} = 25 \times 10^{-3}j0.43s/km \); the zero sequence parameter of the transmission line \( z_{t0} = j1.38\Omega/km \), \( \omega_{c0} = 1.9 \times 10^{-6}j0.43s/km \).

![Diagram of ±1100kV Changji-Xinjiang - Guquan-Anhui UHVDC transmission system](image)

**Table 1. Simulation results of permanent faults under different conditions.**

| \( R_t/\Omega \) | \( l/\% \) | \( U_{set} \) | \( U_m \) | Results          |
|-------------|----------|-------------|----------|-----------------|
| 0           | 0        | 17.89       | 0.000    | Permanent fault |
| 0           | 25       | 18.25       | 0.077    | Permanent fault |
| 0           | 50       | 18.88       | 0.239    | Permanent fault |
| 0           | 75       | 19.43       | 0.266    | Permanent fault |
| 0           | 100      | 19.82       | 0.562    | Permanent fault |
| 50          | 0        | 17.89       | 0.432    | Permanent fault |
| 50          | 25       | 18.25       | 0.577    | Permanent fault |
| 50          | 50       | 18.88       | 0.839    | Permanent fault |
| 50          | 75       | 19.43       | 0.866    | Permanent fault |
| 50          | 100      | 19.82       | 1.162    | Permanent fault |
| 100         | 0        | 17.89       | 0.957    | Permanent fault |
| 100         | 25       | 18.25       | 1.177    | Permanent fault |
| 100         | 50       | 18.88       | 1.439    | Permanent fault |
| 100         | 75       | 19.43       | 2.066    | Permanent fault |
| 100         | 100      | 19.82       | 2.562    | Permanent fault |

From the above simulation results, it can be found that this new criterion scheme can accurately identify permanent faults and leave a sufficient margin.
Table 2. Simulation results of transient faults under different conditions.

| I/% | U_<sub>set</sub> | U_<sub>m</sub> | Results     |
|-----|-----------------|----------------|-------------|
| 0   | 17.89           | 22.89          | Transient fault |
| 25  | 18.25           | 20.25          | Transient fault |
| 50  | 18.88           | 21.88          | Transient fault |
| 75  | 19.43           | 22.43          | Transient fault |
| 100 | 19.82           | 22.82          | Transient fault |

It can be seen from Table 2 that the new criterion can also accurately identify transient faults.

5. Conclusion

In recent years, DC transmission has developed rapidly, and the construction of AC and DC hybrid systems has become more and more common. In order to avoid DC blocking caused by erroneous reclosing under permanent faults on the AC side, the research on smart reclosing is becoming more and more significant. The new criterion of fault type identification proposed in this paper based on the voltage signal can accurately identify the type of fault, and leave enough margin, which greatly reduces the misjudgment area in the traditional criterion, and is of valuable reference for the research of intelligent reclosing.

Acknowledgments

This work is supported by the Science and Technology Project of State Grid Corporation of China: Research on rapid identification of high resistance faults and intelligent reclosing technology for UHV AC/DC near-zone transmission lines

References

[1] Ge Yaozhong, Sui Fenghai, Xiao Yuan. Prediction methods for preventing single-phase reclosing on permanent fault[J]. IEEE Trans. on Power Delivery, 1989, 4(1): 114-121

[2] Lin X, Liu P. Method of distinguishing between instant and permanent faults of transmission lines based on fuzzy decision[C]// International Conference on Energy Management & Power Delivery. IEEE, 1998:455-460.

[3] Radojevic Z M, Shin J R. New One Terminal Digital Algorithm for Adaptive Reclosing and Fault Distance Calculation on Transmission Lines[J]. IEEE Transactions on Power Delivery, 2006, 21(3):1231-1237.

[4] Jamali S, Parham A. New approach to adaptive single pole auto-reclosing of power transmission lines[J]. IET Generation Transmission & Distribution, 2010, 4(1):115-122.

[5] Ahn S P, Kim C H, Aggarwal R K, et al. An Alternative Approach to Adaptive Single-Pole Auto Reclosing in High-Voltage Transmission Systems Based on Variable Dead Time Control[J]. IEEE Power Engineering Review, 2007, 21(4):70-70.

[6] DONG Xin-zhou, CHEN Zheng, HE Xuan-zhou, et al. Optimizing Solution of Fault Location[A]. in: IEEE Power Engineering Society Summer Meeting[C]. 2002.1113-1117.