Fast phase selection method based on transient current for UHV transmission lines

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Abstract: Ultra-high-voltage (UHV) transmission lines have a higher requirement for selecting faulted phases fast and reliably. The coupling relationship between the three phases is analysed in detail. On the basis of the coupling relationship, the principle of faulted phase selection (FPS) is proposed, which utilises the time-domain energy of three-phase transient currents. To remove high-frequency noise and preserve the transient current waveform features invariant, a morphological filter with flat structure element is applied in FPS algorithm. The simulation model of Jindongnan–Nanyang–Jingmen UHV transmission project is established in EMT. The testing results show that the proposed algorithm is feasible and fast (<2 ms) in case of various fault conditions.

1 Introduction

Ultra-high-voltage (UHV) transmission lines have a higher demand to power system transient stability. Fast fault clearance and single-pole autoreclosure are significant to improve the security and stability of the UHV transmission system. The protection utilising transient fault information is able to achieve high-speed even ultra-high-speed operating performance (usually <5 ms). The transient-based protection must provide the fast and exact faulted phase selection (FPS) so that advanced single-pole autoreclosure can be implemented.

The initial travelling wave-based FPS methods can quickly identify the faulted phases [1, 2], but it is defective in its vulnerability to fault arc, small fault inception angle, the wave reflection and refraction. Thus, the fault-generated transient-based FPS schemes have been developed [3, 4], which utilise and extract the fault-type information during a period of time after a fault occurs. Compared to the initial travelling wave-based FPS methods, the transient-based FPS schemes have higher reliability, but slightly slower identification speed.

Many advanced mathematical tools are applied in FPS schemes to obtain better performance. With the good time–frequency localisation, wavelet transform (WT) has been widely used in fault classification [1, 2, 4, 5]. A novel neural network-based technique for phase selection is presented in [3]. In [6, 7], both WT and neural network are used to improve recognition performance. The combination of WT and Bayesian linear discrimination is also employed in [8]. Incorporating the advantages of WT, singular value decomposition (SVD) and Shannon entropy, the technique called wavelet singular entropy is demonstrated in [9], which is immune to the noise in the fault transient. Replacing WT with mathematical morphology (MM), the FPS method can perform in a short data window by combining MM with SVD and Shannon entropy [10]. These FPS schemes all need complicated calculation, which weaken their practical value.

The motivation of this paper is to develop a new FPS approach, which can respond to faults quickly (<2 ms) and is of high reliability within little computation. On the UHV transmission lines, a current transformer is more effective in transforming transient high-frequency signals than capacitor voltage transformer, thus the transient current signal is chosen.

This paper is organised as follows. The basic principle is investigated in Section 2. The FPS algorithm based on MM is described in Section 3. The simulation model of Jindongnan–Nanyang–Jingmen UHV transmission project is established in Section 4, and extensive simulations are carried out to verify the effectiveness of the proposed method. Finally, some conclusions are drawn in Section 5.

2 Basic principle

When a fault occurs on a transmission line, transient current travelling waves will be generated at the fault point, and then they will travel toward the line's busbars. Since the practical transmission line is a parallel multi-conductor system, the transient current travelling wave in the healthy phase is coupled from the faulted phase. The coupling relationship between the three phases is analysed first.

A parallel multi-conductor system including m and n conductors is shown in Fig. 1. Supposing the earth is an ideal conductor, the self-surge impedance $Z_{m}$ and the mutual surge impedance $Z_{mn}$ of conductor $m$ are calculated as the equation below, respectively [11]:

$$Z_{m} = 60 \ln \frac{2h_{m}}{r_{m}}$$

$$Z_{mn} = 60 \ln \frac{D_{mn}}{d_{mn}}$$

where $h_{m}$ is the height above ground; $r_{m}$ is the radius of conductor $m$ (considering bundle conductors, $r_{m}$ should be equivalent geometric mean radius); $D_{mn}$ is the distance from conductor $m$ to the image $n'$ of conductor $n$; and $d_{mn}$ is the distance from conductor $m$ to conductor $n$.

When fault-generated travelling wave propagates along conductor $m$, because of the existence of the electromagnetic field, coupling wave will appear in the parallel conductor $n$. The magnitude of coupling wave depends on the coupling coefficient $k_{m2n}$:

$$k_{m2n} = \frac{Z_{mn}}{Z_{m}} = \frac{\ln(D_{mn}/d_{mn})}{\ln(2h_{m}/r_{m})}$$

where the subscript $m2n$ represents conductor $m$ as the faulted phase and conductor $n$ is the coupled phase.

On the basis of the transmission tower structure and conductor layout, each coupling coefficient between the three phases can be calculated, which determines the magnitude of coupling travelling wave. The phase conductor layout formats of extra HV/UHV
transmission lines are usually horizontal, vertical and triangle. The three-phase conductors of Jindongnan–Nanyang–Jingmen UHV transmission project in China are arranged in a triangle, which is depicted in Fig. 2. The tower type is ZMP2; the conductors are approximately evenly transposed; and the ground wires are segmented grounding.

Thus, the coupling coefficients between the three phases can be obtained as follows: \( k_{B2A} = k_{C2B} = 0.1678 \), \( k_{A2B} = k_{C2A} = 0.1295 \), and \( k_{A2C} = k_{B2C} = 0.1742 \). The coupling coefficients are all <0.2. It is concluded that the transient current magnitude coupled in the healthy phase is much less than the one generated by a fault in the faulted phase.

The fault component of phase current is used in the FPS scheme, which is calculated in the equation below:

\[
\Delta i_p(k) = i_p(k) - i_p(k - N) \quad (4)
\]

where \( \phi \) represents phases \( A, B \) or \( C \); \( N \) is the sampling number in one power frequency period.

According to fault boundary conditions and the coupling relationship between the three phases, fault-type characteristics can be summarised as follows:

(a) Zero mode \( i_0 \) distinguishes whether the fault is grounded or not. For grounding faults, \( i_0 \) is generally large. However, \( i_0 \) of non-grounding faults is very small, theoretically equal to 0.

(b) In grounding faults, for single-phase grounding fault, the faulted phase has the maximum transient current. The transient currents of the other healthy phases are both generated by a fault. Therefore, the ratio between the transient current magnitudes of the two phases is <2.5. If the transient current magnitudes of the two phases are both nearly equal to 0, single-phase grounding fault can also be identified.

For phase-to-phase grounding fault, the transient current of the healthy phase is minimum. The transient currents of the other two phases are both generated by a fault. On basis of the coupling coefficients between the three phases, the smaller transient currents in two faulted phases are larger than 2.5 times the one in healthy phase.

(c) In non-grounding faults, for phase-to-phase fault, the healthy phase has the minimum transient current, and the transient currents of two faulted phases are near to be equal. For three-phase fault, the maximum transient current and the middle one in three phases have usually a large difference in magnitude.

On the basis of above analyses, characteristics of various faults can be concluded in Table 1.

### Table 1 Characteristics of various faults

| Fault type                      | Zero-mode current | Fault component of phase current |
|--------------------------------|-------------------|---------------------------------|
| phase-A grounding fault (Ag)    | \( i_0 \neq 0 \)   | \( |\Delta A| = \text{maximum, } |\Delta B|/|\Delta C| < 2.5 \) |
| phase-B-to-phase-C grounding fault (BCg) | \( i_0 \neq 0 \)   | \( |\Delta A| = \text{maximum, } |\Delta B|/|\Delta C| \leq 2 \) and \( |\Delta C| > 0 \) |
| phase-B-to-phase-C fault (BC)   | \( i_0 = 0 \)      | \( |\Delta A| = \text{minimum, } |\Delta B|/|\Delta C| > 2.5 \) |
| three-phase fault (ABC)         | \( i_0 = 0 \)      | \( |\Delta A| = \text{minimum, then } |\Delta B|/|\Delta C| = 0 \) |

To highlight the fault-type characteristics, the time-domain energy of transient current is chosen as the discriminating quantity. Transient current is high-frequency signal, which is easily influenced by high-frequency noise. Thus, before the time-domain energy of transient current is calculated, an MM filter (MMF) is used to remove high-frequency noise and preserve the transient current waveform features invariant.

#### 3.1 MM filter

MM is a non-linear technique with high accuracy and low calculation volume, which focuses on the shape and size of signals in the time domain and needs a smaller information window [12].

MM has two basic erosions and dilation operators, based on which other hybrid operators such as opening and closing are defined. The opening operator smoothes the sharp edges of the positive impulses and the closing one fills the narrow valleys and gaps of the negative impulses. The combination of opening and closing operators can be used to derive different MMFs [12].

Assuming that \( f(n) \) is the input signal and \( g(n) \) is a structural element (SE), the MMF used in this paper is defined in (5), which has a better effect than other filters in terms of noise removal.

\[
\text{MMF}(n) = \frac{f(n) \ast (f \ast g)(n) + f(n) \ast (f \ast g)(n)}{2} \quad (5)
\]

where \( \bullet \) shows the closing operator and \( \ast \) shows the opening operator.

Depending on the problem to be solved, the SE can have different shapes and sizes. In this paper, flat SE is employed. The value of flat SE is 0 within its definition domain, so it has only one pending parameter, that is, the size of SE. When the size is 7, the processing results of some typical signals by the MMF are shown in Fig. 3. It is clearly observed that the MMF could effectively remove impulse noise and preserve the intrinsic characteristics of step and ramp signals. Most of the fault-generated travelling waves present themselves as quasi-step signals [13]. Therefore, the MMF
3.2 FPS algorithm

In terms of the fault-type characteristics in Section 2, an FPS algorithm is constructed, which compares the relative energy of three-phase transient currents.

The time-domain energy of transient current is calculated according to the equations below:

\[ E_{\phi} = \sum_{n=0}^{N_{\phi}-1} \Delta i_{\phi}^2(n) \]  
\[ E_0 = \sum_{n=0}^{N_{\phi}-1} i_0^2(n) \]

where \( N_{\phi} \) is the width of the data window.

The relative energy is defined as follows:

\[ e_{\phi} = \frac{E_{\phi}}{E_{A}, E_{B}, E_{C}} \]
\[ e_0 = \frac{E_0}{E_{A}, E_{B}, E_{C}} \]

The flowchart of the proposed phase selection method is depicted in Fig. 4.

4 Simulation and evaluation

The simulation model of Jindongnan-Nanyang-Jingmen UHV transmission project is established in alternative transient program/ electromagnetic transient program (ATP/EMTP), as shown in Fig. 5. The frequency-dependent transmission line model is employed, and the line parameters are given in Fig. 2. A stray capacitance of 0.01 μF is assumed at each busbar. Each line parameter is shown in Tables 2 and 3. The protected line is MN, and the FPS algorithm is arranged at M end. The sampling rate is 400 kHz. The width of data window \( N_{\phi} \) is 512 (1.28 ms). The size of SE is 7. The four thresholds are as follows: \( \epsilon_0 = 0.001, \epsilon_1 = 0.1, \epsilon_2 = 0.005 \) and \( \epsilon_3 = 2.5 \).

In the case of close-up phase-A grounding fault (Ag), fault location is 1 km from busbar M, fault resistance is 300 Ω, and the fault inception angle of phase A is 5°. The transient current waveforms of zero mode and three phases, together with the MMF output results are all demonstrated in Fig. 6. The MMF removes them completely. So the reliability of FPS algorithm is improved. The time of FPS data window is 1.28 ms, plus the data processing time, the total FPS time will be <2 ms. Thus, the FPS algorithm is rather rapid.

The relative energy values \( e_0 = 1.86, e_A = 1, e_B = 0.033 \) and \( e_C = 0.033 \), according to the FPS algorithm, phase-A grounding fault can be identified accurately.

For the remote phase-A-to-phase-B grounding fault (ABg), fault location is 358 km from busbar M, fault resistance is 300 Ω, and the fault inception angle of phase A is 90°. From Fig. 7, it is pretty obvious that the MMF has good filtering effect for large impulse signal. The relative energy values are calculated out at 1.6
ms, $e_0 = 0.011$, $e_A = 1$, $e_B = 0.80$ and $e_C = 1.9 \times 10^{-4}$, which accords with the characteristics of phase-to-phase grounding fault. As a result, the exactly faulted phases are determined.

The influence of fault resistance is studied in this paper. The simulation results are shown in Table 4, which indicates that there is almost no effect on the FPS method. With the increase of the resistance, zero mode becomes smaller.

The influences of various fault inception angles are also simulated. Simulation results in Table 5 show that the proposed FPS method can operate accurately in the cases of small fault inception angles. For remote faults, with the decrease of the inception angle, zero mode has a smaller magnitude.

### 5 Conclusions

On the basis of the coupling relationship between the three phases in UHV transmission lines, the FPS principle and algorithm are presented, utilising the time-domain energy of three-phase transient currents. An advanced MMF is proved to be effective to process transient currents. A lot of simulations have been conducted, which demonstrates that the target responding to faults quickly (<2 ms) and reliably within little computation has been achieved in the proposed FPS method.

Applying this FPS method in a systematic transient-based protection scheme will be the next research work.

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Fig. 7  Transient current waveforms and their MMF outputs in the case of remote fault

Table 4  Simulation results with different fault resistances (fault location: 179 km from busbar M and fault inception angle of phase A: 45°)

| Fault resistance, Ω | Fault type | \( e_0 \) | \( e_A \) | \( e_B \) | \( e_C \) | FPS result |
|---------------------|------------|---------|---------|---------|---------|-------------|
| 0                   | Ag         | 1.27    | 1       | 0.005   | 0.006   | Ag          |
|                     | ABg        | 0.008   | 0.85    | 1       | 1.4 \times 10^{-4} | ABg        |
|                     | AB         | 1.4 \times 10^{-12} | 1   | 0.99    | 2.2 \times 10^{-11} | AB          |
|                     | ABC        | 4.5 \times 10^{-16} | 0.80 | 1       | 0.015   | ABC         |
| 300                 | Ag         | 1.26    | 1       | 0.005   | 0.006   | Ag          |
|                     | ABg        | 0.006   | 0.96    | 1       | 1.1 \times 10^{-5} | ABg        |
|                     | AB         | 4.2 \times 10^{-14} | 0.99 | 1       | 1.1 \times 10^{-10} | AB          |
|                     | ABC        | 4.5 \times 10^{-16} | 0.80 | 1       | 0.015   | ABC         |

Table 5  Simulation results with various fault inception angles (fault type: Ag; fault location: the distance from busbar M; and fault resistance: 0 Ω)

| Inception angle, ° | Fault location, km | \( e_0 \) | \( e_A \) | \( e_B \) | \( e_C \) | FPS result |
|--------------------|--------------------|---------|---------|---------|---------|-------------|
| 90                 | 1                  | 1.81    | 1       | 0.030   | 0.030   | Ag          |
|                    | 179                | 1.30    | 1       | 0.007   | 0.007   | Ag          |
|                    | 358                | 0.81    | 1       | 0.013   | 0.013   | Ag          |
| 45                 | 1                  | 1.82    | 1       | 0.031   | 0.031   | Ag          |
|                    | 179                | 1.27    | 1       | 0.005   | 0.006   | Ag          |
|                    | 358                | 0.76    | 1       | 0.012   | 0.013   | Ag          |
| 5                  | 1                  | 1.87    | 1       | 0.034   | 0.034   | Ag          |
|                    | 179                | 1.16    | 1       | 0.002   | 0.003   | Ag          |
|                    | 358                | 0.58    | 1       | 0.018   | 0.019   | Ag          |

7  References

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