Research on Adaptive Reclosing Discriminant Method Based on LMD Sample Entropy

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Abstract. Based on the adaptive time-frequency analysis characteristics of local mean decomposition and the nonlinear quantization ability of sample entropy, an adaptive reclosing discriminant method based on LMD sample entropy is proposed. Firstly, the local mean decomposition method is applied to decompose the original signal of the transmission line fault into several product function components (PF component). Then calculate the sample entropy of the first three PF components to achieve feature quantization of the PF component. Finally, the sum of the sample entropy of first three PF components is used as the eigenvalue to distinguish the fault type of the transmission line. Obtained from the simulation results, the method can identify the type of fault.

1. Introduction
The fault rate of the transmission line is the highest in the whole power system component [1]. The reclosing device can quickly restore normal power supply and effectively improve the stability of power system operation. So it is necessary to judge whether the fault nature of the line is permanent or transient before reclosing action. Electric power researchers at home and abroad have done a lot of research on adaptive reclosing [2-4]. In terms of the type of fault nature, the method of using the steady-state power-frequency voltage of the fault phase and the non-fault phase accounts for the majority [5].

The secondary arc voltage waveform distortion of the transient short-circuit ground fault is very serious, contains a large amount of high-frequency components, and the content of each frequency component is unstable and changes with time. In this paper, permanent fault and transient fault are distinguished according to the complexity of fault phase voltage signal after tripping. The local mean decomposition (LMD) is used to decompose the fault signal into PF components with physical meaning, and the sample entropy is used to calculate the complexity of PF components as eigenvalues to distinguish the fault properties.

2. Analysis of Arc Characteristics
According to the period of fault arc generation, the transient short circuit grounding fault arc can be classified as: the primary arc from the occurrence of the fault to the protection action on both sides of the line and the secondary arc from the protection action to the complete extinguishing of the arc.
A large amplitude short-circuit current flows through the primary arc. Due to the continuous energy support of the system power supply, the arc length of the arc is relatively stable. Moreover, the arc drop is mainly concentrated on the arc column, and the pressure drop at the arc angle is negligible. There is a repeated process of reburning and extinguishing of the secondary arc. Only when the actual arc voltage is no longer greater than the arc reburning voltage can the secondary arc be completely extinguished [6].

The voltage waveforms of the primary arc and the secondary arc are shown in Fig.1 and Fig.2.

![Figure 1. Voltage waveform of secondary arc](image1)

![Figure 2. Voltage waveform of primary arc](image2)

3. Simulation of single-phase ground fault
Using the EHV transmission line with a length of 478.9km and a voltage of 750kV as a practical example of simulation.

(1) The single-phase grounding transient fault of transmission line is simulated by ATP/EMTP simulation software, which is shown in Fig.3. The waveform of the fault phase terminal voltage is shown in Fig.4.
The fault occurs in 50ms, and the circuit breaker at both ends jumps off in 100ms. The arc extinguishing time is 300 ms, and the reclosing time is 800 ms, sampling frequency is 10kHz. A phase is taken as the fault phase, and the phase voltage waveform of the transmission line in different places and in the case of different grounding resistance is simulated.

(2) The single-phase grounding permanent fault of transmission line is simulated by ATP/EMTP simulation software, as shown in Fig.5. The setting fault occurs in 50ms, and the circuit breaker at both ends jumps off at 100ms, and the sampling frequency is 10kHz. The waveform of the fault phase terminal voltage is shown in Fig.6.
Figure 5. Simulation Model of permanent single-phase grounding short Circuit Fault

Figure 6. The waveform of the fault phase terminal voltage

4. Theoretical background

4.1. Local mean decomposition

The basic idea of LMD method is to adaptively decompose complex nonlinear nonstationary signals into finite product function (PF) components. For signal $x(t)$, the LMD decomposition steps [7] are as follows.

1. By calculating all the local extreme points of $x(t)$, the local mean $m_i$ and envelope estimation values $a_i$ of two adjacent extreme points $n_i$ and $n_{i+1}$ can be obtained as follows. For all local mean values, the local mean function $m_{i1}(t)$ is obtained by moving average method, and the envelope estimation function $a_{i1}(t)$.

2. Remove $m_{i1}(t)$ available $h_{i1}(t)$ from signal $x(t)$, then decoupling $h_{i1}(t)$.

$$s_{i1}(t) = \frac{h_{i1}(t)}{a_{i1}(t)}$$

Repeat steps (1)-(2) until $s_{i1}(t)$ is a pure frequency modulation signal, that is, the envelope estimation function $a_{i(n+1)}(t)$ of $s_{i1}(t)$ is equal to 1.
(3) At the end of the iteration, the envelope signal $a_1(t)$ can be obtained.

$$a_i(t) = a_{i1}(t)a_{i2}(t)\cdots a_{in}(t) = \prod_{k=1}^{n}a_{ik}(t)$$  \hspace{1cm} (2)

In the formula, $k$ is the number of iterations.

(4) The first PF component of the signal $x(t)$ is

$$P_{r1}(t) = a_1(t)s_{1n}(t)$$  \hspace{1cm} (3)

The instantaneous amplitude is $a_1(t)$ and the instantaneous frequency is

$$f_1(t) = \frac{1}{2\pi} \frac{d}{dt} \left( \arccos(s_{1n}(t)) \right)$$  \hspace{1cm} (4)

(5) Repeat steps (1)-(4) until $u_k(t)$ monotone

At this point, the original signal $x(t)$ can be represented as

$$x(t) = \sum_{i=1}^{k} P_{r1}(t) + u_k(t)$$  \hspace{1cm} (5)

4.2. Sample entropy

Sample entropy (SE) is an improvement of approximate entropy algorithm, and the accuracy of the result is better than that of approximate entropy. The more complex the analysed sequence, the larger the corresponding SE value. On the contrary, the higher the self-similarity of the sequence, the smaller the SE value. The sample entropy needs only a small amount of data to quantitatively analyse the self-similarity and complexity of time series data, so it has been widely used in the field of engineering [8]. At present, most scholars use local mean decomposition method and information entropy in rotating machinery fault diagnosis, but less in transmission line fault diagnosis.

5. Algorithm simulation analysis

It can be seen from a large number of simulated voltage waveforms that the single-phase grounding fault occurs in the transmission line, the grounding resistance and the fault occurrence point are different, and the voltage waveform collected at the transmission end and the receiving end will be different from that of the circuit breaker at the first arc stage and at the moment when the circuit breaker is disconnected, but the secondary arc stage will not be affected by the difference between the fault point and the transition resistance after the circuit breaker has been disconnected for two power frequency cycles. Therefore, in order to avoid the influence of the transient over-voltage when the circuit breaker is open, the fault signal of the transient fault and the permanent fault is collected at 10000 Hz after two power frequency cycles. A total of 18 sets of data were collected. Using LMD to decompose the fault signal, the decomposition results of one set of data of transient and permanent faults are shown in Fig.7 and Fig.8.

![Figure 7. The LMD decomposition results of permanent fault signals](image-url)
From the results of LMD decomposition, it can be seen that the information of fault signal is mainly concentrated in the first three PF components, so the first three PF components are selected as the analysis object. Each group of fault signals is decomposed by LMD, the sample entropy of each PF component is obtained, and the sum of the sample entropy of the first three PF components is used as the characteristic value. Table 1 lists the sample entropy and entropy sum of the first three PF components of each group of fault signals.

| Transition resistance /Ω | Occurrence point | Fault type       | The sample entropy of the first three PF components | The sum of sample entropy |
|--------------------------|------------------|------------------|------------------------------------------------------|---------------------------|
|                          | Line head        | Transient Fault  | 0.7987 0.4947 0.0918 | 1.3852                    |
|                          |                  | Permanent Fault  | 0.0042 0.0038 0     | 0.008                     |
| 0                        | Line midpoint    | Transient Fault  | 0.9821 0.4867 0.1282 | 1.597                     |
|                          |                  | Permanent Fault  | 0.3285 0.0356 0.0087 | 0.3728                    |
|                          | Line end         | Transient Fault  | 0.6578 0.5643 0.1084 | 1.3305                    |
|                          |                  | Permanent Fault  | 0.3453 0.0682 0.0060 | 0.4195                    |
|                          | Line head        | Transient Fault  | 0.6970 0.4814 0.0543 | 1.2327                    |
|                          |                  | Permanent Fault  | 0.0893 0.0057 0.0025 | 0.0975                    |
| 50                       | Line midpoint    | Transient Fault  | 0.7189 0.4179 0.0518 | 1.1886                    |
|                          |                  | Permanent Fault  | 0.3152 0.0311 0.0008 | 0.3471                    |
|                          | Line end         | Transient Fault  | 0.6193 0.4875 0.1418 | 1.2486                    |
|                          |                  | Permanent Fault  | 0.2354 0.0124 0.0035 | 0.2513                    |
|                          | Line head        | Transient Fault  | 0.5917 0.5226 0.0152 | 1.1295                    |
|                          |                  | Permanent Fault  | 0.2319 0.0094 0.0058 | 0.2471                    |
| 100                      | Line midpoint    | Transient Fault  | 0.5731 0.3894 0.1064 | 1.0689                    |
|                          |                  | Permanent Fault  | 0.3243 0.0416 0.0111 | 0.3770                    |
|                          | Line end         | Transient Fault  | 0.5811 0.4975 0.0762 | 1.1548                    |
|                          |                  | Permanent Fault  | 0.2319 0.0094 0.0058 | 0.2471                    |

It can be seen that the LMD sample entropy of the line fault signal under transient fault is higher than that in the permanent fault state, because the fault of the secondary arc voltage waveform is very serious when the transient fault occurs. It contains a large number of high-frequency components, and
the content of each frequency component is unstable. As time changes, the more information the fault signal contains, the larger the entropy value of the signal sample.

It can be seen from Table 1 that when a single-phase ground fault occurs in a transmission line with a shunt reactor, the sum of sample entropy of different fault types is different and there is a certain gap between them. The threshold is set to 1. When the sum of sample entropy is greater than the threshold, it is determined to be a transient fault. And when it is less than this threshold, it is determined to be a permanent fault. Therefore, the sum of sample entropy can be used to distinguish between transient faults and permanent faults. Fig. 9 is the curve of sample entropy sum for transient and permanent faults in transmission lines at different locations and different transition resistances.

Figure 9. The curve of sample entropy sum under different conditions for different faults

6. Conclusion
Based on LMD algorithm and sample entropy theory, a fault feature extraction method for transmission line based on LMD sample entropy is proposed. The fault feature extraction of single-phase grounding short-circuit signal of transmission line is carried out by using this method. The feasibility of the proposed method is verified by the simulation results, and the following conclusions are drawn.

(1) The signal characteristics of single-phase grounding short circuit of transmission line extracted by LMD sample entropy can be used to judge the fault type of transmission line and accurately reflect the fault type.

(2) LMD sample entropy has strong signal representation ability and can be applied to feature extraction of complex signals.

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