Fault location of hybrid distribution lines based on empirical mode decomposition

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Abstract. This paper presents a fault location method for cable hybrid distribution lines based on EMD and TEO algorithm. Firstly, the fault signal is decomposed by EMD. Then, the transient energy spectrum of high frequency imf1 component is obtained by using Teager energy operator. The first energy singularity is the time when the fault initial traveling wave head reaches the detection point. Finally, the fault location is carried out according to the fault search algorithm based on time variable. According to the simulation results, EMD and TEO methods have better fault extraction ability and higher accuracy in fault location.

1. Introduction

At present, on the basis of single overhead line, more and more hybrid distribution lines of cable and overhead line have been developed in China’s distribution network. However, cable and overhead lines often fail due to quality, environment and other reasons. When the distribution line fails, the reliability of power supply is reduced, so it is necessary to quickly and accurately determine the location of the fault point.

2. Fault traveling wave propagation process of cable hybrid distribution lines

As shown in Figure 1, the hybrid distribution line is represented by a section of cable and overhead line mixed connection line, and the buses on both sides are represented by M and N respectively. The connection point of cable and overhead line is represented by P, and the fault point is represented by F. MP section is cable section and PN section is overhead section. When the fault occurs at point F, the fault traveling wave generated at point F moves to the M-terminal and N-terminal of the bus on both sides. After the fault traveling wave moves to the M end of bus, it will refract and reflect. The refracted wave continues to move forward, while the reflected wave changes direction and moves toward the N end of bus. When the fault traveling wave moving to the N-end of bus passes through the line connection point P, it will also refract and reflect. The refracted wave will continue to move to the N-section of bus. When it moves to the N-end of bus, it will refract and reflect again. The refracted wave will continue to move forward and the reflected wave will move toward the N-end of bus. The fault traveling wave reflected at the line connection point P moves towards the bus m end, and refracts and reflects again at the fault point F. The fault traveling wave continuously refracts and reflects at the discontinuities of wave impedance until it decays to zero [1].

When a fault occurs on the transmission line, when the fault traveling wave generated by the fault point moves along the bus on both sides of the transmission line, serious refraction and reflection will
occur, which will increase the difficulty of accurately obtaining the initial traveling wave head of the fault.

![Figure 1. Fault traveling wave propagation process of cable hybrid distribution lines.](image)

3. Fault data processing based on empirical mode decomposition
The point of wave impedance discontinuity in cable hybrid distribution line includes not only the bus at both ends, but also the connection point between overhead line and cable. When the fault traveling wave moves from the fault point to both sides, it is refracted and reflected at the discontinuous point of wave impedance, which makes it more difficult to obtain the fault initial traveling wave head accurately.

3.1. Empirical mode decomposition algorithm
Empirical mode decomposition (EMD)[2-3] decomposes complex non-stationary signals into multiple stationary time-domain signals, namely intrinsic mode function (IMF). There is no energy loss in the process of decomposition using EMD algorithm, and the decomposition process is adaptive. The number of decomposed time-domain signals is determined by the original non-stationary signals. Each eigenmode function decomposed should satisfy the following two conditions:

1. In the whole signal length, the number of extreme points and zero crossing points should be the same, or one difference.
2. At any time point, the upper envelope formed by the maximum point and the lower envelope formed by the minimum point are symmetrically distributed on both sides of the time axis.

3.2. Teager energy operator
Teager energy operator (TEO)[4-5] is a nonlinear energy operator, which can effectively extract the instantaneous frequency and amplitude of the signal, and can reflect the instantaneous energy value of the signal.

For continuous signal $f(t)$, the energy operator $\psi$ can be defined as:

$$
\psi[f(t)] = \left[ \frac{df(t)}{dt} \right]^2 - f(t) \frac{d^2 f(t)}{dt^2}
$$

(1)

For the discrete signal $f(n)$, the energy operator $\psi$ can be defined as:

$$
\psi[f(n)] = f^2(n) - f(n-1)f(n+1)
$$

(2)

TEO can reflect the instantaneous change of signal. The Teager energy value increases with the increase of the amplitude or frequency change rate of the signal. Therefore, the TEO energy operator can be used to detect and identify the singularity of the fault signal.
4. Fault location principle of hybrid distribution line

The steps of hybrid distribution line fault location are as follows[6-8]:

(1) Determine the electrical composition of MN, the length of each section of the line (set the length of MP section of overhead line as L_{MP}, the length of PQ section of cable line as L_{PQ}, and the length of QN section of overhead line as L_{QN}), the traveling wave velocity v_{1} in the overhead line and the traveling wave velocity v_{2} in the cable.

(2) The travel time of traveling wave on each section of line is calculated one by one. (suppose that the traveling wave motion time of MP section of overhead line, PQ section of cable line and QN section of overhead line in Figure 2 is t_{a} = L_{MP} / v_{1}, t_{b} = L_{PQ} / v_{2} and t_{c} = L_{QN} / v_{1} respectively)

(3) Suppose that the time for the initial traveling wave to move to the measuring points M and N at both ends is t_{1} and t_{2} respectively, and the time difference Δt = t_{1} - t_{2}.

\[ t_{1} - t_{2} = \Delta t \]  
\[ t_{1} + t_{2} = t_{a} + t_{b} + t_{c} \]  

By combining the above two equations, the time t_{1} and t_{2} for the initial traveling wave head to move to the measuring points M and N at both ends can be solved.

\[ t_{1} = \frac{1}{2} \left( t_{a} + t_{b} + t_{c} + \Delta t \right) \]  
\[ t_{2} = \frac{1}{2} \left( t_{a} + t_{b} + t_{c} - \Delta t \right) \]  

(4) When t_{1} < t_{a}, the fault point can be located in MP section of overhead line, and the distance between the fault point and M can be obtained by using \( d = v_{1}t_{1} \); when t_{a} < t_{1} < t_{a} + t_{b}, the fault point can be located in PQ section of cable line, and the distance between the fault point and M can be obtained by using \( d = x_{1} + v_{2}(t_{1} - t_{a}) \); when t_{a} + t_{b} < t_{1} < t_{a} + t_{b} + t_{c}, the fault point can be located in MN in the QN section of overhead line, the distance between the fault point and the measuring end M can be obtained by using. Similarly, the comparison can be started from the N-end of the measuring point, which will not be repeated here.

5. Simulation analysis

5.1. Simulation model
The model of 35kV Cable hybrid distribution line is established by PSCAD simulation software and its electrical topology is shown in Figure 2. MP section is overhead line section with length of L_{MP} = 20km, PQ section is cable section with length of L_{PQ} = 10km, QN section is overhead line section with length of L_{QN} = 20km, and total length of line MN is L_{MN} = 50km.

5.2. Fault simulation
The single-phase ground fault occurs at point F of the overhead line. The distance between the fault point F and the M end of the bus is 42km. The fault point is located in the QN section of the overhead line. The location of the fault point is shown in Figure 2. The simulation step is 1 μs and the sampling frequency is 1MHz.
Figure 3. IMF1 component measured at M-terminal of bus.

Figure 4. IMF1 component measured at N-terminal of bus.

Figure 5. Teager energy spectrum of IMF1 component measured at M-terminal of bus.
Through the analysis of the above simulation waveforms, it can be concluded that the time when the fault initial traveling wave first reaches the M-terminal of bus is 0.000177s, and the time when the fault initial traveling wave first reaches the N-terminal of bus is 0.000028s. Through calculation, the time difference between the fault initial traveling wave and the M-terminal of bus is $0.000177 - 0.000028 = 0.000149s$. According to the fault location principle of the hybrid distribution line and the known traveling wave velocity in the overhead line and cable line, it can be judged that the fault point is located in the QN section of the overhead line, and the distance between the fault point and the M end of the bus is 41.88km, which is 0.12km different from the actual fault point, and the error is 0.24%, which meets the requirements of location accuracy.

6. Conclusion

The fault signal analysis method based on EMD and TEO algorithm can effectively obtain the time when the initial traveling wave head of the fault moves to the fault detection point, thus providing accuracy guarantee for cable hybrid fault location.

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