Transmission Line Fault Location Based on Improved Algorithm of Electromagnetic Time Reversal

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ABSTRACT For most traditional fault location methods, the fault type needs to be known in advance or there may be dead zones using the decoupled modulus. To solve the problems, an improved algorithm based on electromagnetic time reversal is proposed. The improved algorithm can realize fault location by using the coupling signal in the non-fault phase of the transmission line, so fault location can be realized effectively even when the fault phase is unknown. The feasibility of using non-fault phase coupled signals to locate faults is theoretically verified. A 750kV overhead transmission line model is established by ATP-EMTP to obtain the fault signal at the observation point. The fault signal is time reversed and then connected to the observation point as an injection source. Each hypothetical fault location is traversed and its current is calculated by the BLT super-matrix equation. The 2-norm based on current energy is proposed as the criterion, and the position with the largest norm is the fault location. The simulation results show that the algorithm is not affected by the fault types, transition resistance and the initial phase angles of the power sources on both sides, and has high accuracy.

INDEX TERMS BLT super-matrix equation, coupling current, electromagnetic time reversal, fault location.

I. INTRODUCTION
As an important part of the power system, the fault of transmission lines will affect the normal transmission of electric energy. If the fault point cannot be found and solved in time, it may cause a power outage and economic losses. In extreme cases, if the primary load also loses power, it will cause social chaos and huge economic losses. So it is of great significance for ensuring safe and reliable power supply to determine the fault location and eliminate the hidden trouble in time [1].

The traditional methods of fault location mainly include traveling wave method [2], [3], fault analysis method [4], [5], and natural frequency method [6]–[8]. Traveling wave method uses wave velocity and the time of fault traveling wave propagating to the observation point for fault location. It is simple and is not affected by fault type and transition resistance, but the identification of traveling wave head is difficult due to of the complex catadioptric reflection. Fault analysis can be divided into single-terminal method and double-terminal method. The ranging accuracy of the single-terminal method is easily affected by transition resistance and system operation mode. The double-terminal method needs to establish data communication channel between the two ends of the line, which requires high synchronization of data at both ends. Natural frequency method uses frequency domain information to achieve fault location by analyzing the frequency spectrum of fault traveling wave signals, it has simple principle and good adaptability, but its accuracy is directly affected by natural frequency extraction.

Time Reversal (TR) theory was developed first in the acoustics field [9], and then it was extended to the field of electromagnetic waves by Lerosey et al. [10]. Electromagnetic Time Reversal (EMTR) theory was gradually applied in the field of transmission line fault location. Razzaghi first proposed the energy criterion theory based on EMTR [11] and proved the feasibility in fault location of lossless transmission lines. The effect of losses on EMTR has been studied and three types of reversal model have been proposed in [12]. The mirror minimum energy and a time domain waveform similarity [13], [14] have been used as fault location criterion.
Based on the energy criterion, the amplitude criterion and EMTR algorithm based on the correlation of transfer function are proposed in [15] and [16]. Most of the above literature is focused on single-phase circuits, and the reversal model is required to be consistent with the model at the time of fault occurrence, which cannot be used in the case of unknown fault phase. The theoretical correctness of EMTR in line fault location under various conditions is demonstrated in [17]. Electromagnetic time reversal is used to locate partial discharge in power cable [18], [19]. Without considering the reflected wave, the fault location of double circuit line on the same pole and series compensation line is achieved by using electromagnetic time reversal for two-terminal fault current after decoupling [20], [21]. However, the decoupled single modulus signal cannot reflect all the fault types, if multiple modulus signals are used, the hardware cost will be greatly increased. The electromagnetic time reversal method and wavelet transform are combined for fault location of flexible HVDC transmission lines [22]. The reversal model constructed in this paper is a lossless mirror line. It causes the inconsistent wave velocity between the reversal model and the fault line model, resulting in certain errors. An EMTR fault location algorithm based on the forward current in the frequency domain has been proposed in [23], which uses a lower sampling frequency and reduces the hardware cost. But the algorithm needs to use the positive sequence component of the forward current in the frequency domain, so there may have location errors for unbalanced lines.

From above it can be seen that some fault location methods use decoupled signal and can’t identify all kinds of faults. Others use the current signal of the fault phase, which requires the fault phase information in advance. To solve the above problems, this paper proposes an improved EMTR fault location algorithm by using the non-fault phase coupled current. Compared with the traveling wave method, the fault location method in this paper only uses single-ended current data which has no need to consider the time synchronization problem and avoids the difficulty of traveling wave head identification; Most decoupling methods may have dead zone due to the single modulus cannot reflect all fault types. But the improved EMTR algorithm proposed in this paper does not require decoupling, which avoids the dead zone problem; In addition, the improved algorithm can use the coupled currents in the non-fault phase to achieve fault location, effectively solving the problem that the faulty phase is unknown when the fault occurs. In the future, the method needs to be further studied in the application of multi-branch lines. The effectiveness of the algorithm is verified by the simulations for 750kV transmission line.

II. IMPROVED EMTR ALGORITHM

A. THEORETICAL BASIS OF EMTR

EMTR refers to the reversal of the measured signal on the time axis, that is changing the direction of the time axis, and then reinjecting it into the measured system. The time reversal (TR) process is achieved through mathematical equations, which is a necessary prerequisite for the EMTR method. This process can be expressed as \( x(t) \rightarrow x(-t) \), where \( x(t) \) is measured signal and \( x(-t) \) is reversal wave. The injected signal will produce the phenomenon of simultaneous focusing in time and space at the original signal source. The premise of using EMTR technology is that the system satisfies the invariance of EMTR. Inversing function after EMTR is substituted into the original analytic equation, and the equation is still valid.

The relationship between voltage and current on the multi-conductor lossless transmission line can be described by the telegraph equation, which is expressed as [11]

\[
\frac{\partial}{\partial x} V(x,t) + L \frac{\partial}{\partial t} I(x,t) = 0 \\
\frac{\partial}{\partial x} I(x,t) + C \frac{\partial}{\partial t} V(x,t) = 0
\]  

(1)

where, \( x \) represents the longitudinal direction of the transmission line. \( V(x,t) \) and \( I(x,t) \) respectively represent the multi-conductor voltage and current matrix at position \( x \) when time is \( t \). \( L' \) and \( C' \) respectively represent the per-unit-length matrices of the inductance and capacitance of the multi-conductor transmission line.

The EMTR transformation \((t \rightarrow -t)\) is applied to the above equation, and the below equation can be obtained.

\[
\frac{\partial}{\partial x} V(x,-t) + L' \frac{\partial}{\partial (-t)} (-I(x,-t)) = 0 \\
\frac{\partial}{\partial x} (-I(x,-t)) + C' \frac{\partial}{\partial (-t)} V(x,-t) = 0
\]  

(2)

During the reverse propagation of inverting current, the motion direction of charge will change. Therefore, the current should be negative. It can be seen from (2) that if \( V(x,t) \) and \( I(x,t) \) are solutions of the telegraph equation, then \( V(x,-t) \) and \( -I(x,-t) \) after electromagnetic time reversal are also solutions of the telegraph equation. For multi-conductor lossless transmission lines, the telegraph equation satisfies the invariance of EMTR. For lossy wires, the fault location also can be accurately identified [12].

B. REVERSAL PROCESS OF IMPROVED EMTR ALGORITHM

At present, the existing literature which adopts EMTR algorithm requires the reversal stage and the forward propagation stage to be consistent in the fault type, fault phase, and so on. In practice, it can be judged whether the fault type is single-phase fault or multi-phase fault according to the action of relay protection devices. However, the fault phase needs to be judged by other algorithms, which are difficult to obtain directly. In order to make the EMTR algorithm applicable to the situation where the fault phase is unknown, the propagation characteristics of the coupling signals are studied to analyze the feasibility of using it to achieve fault location.

For transmission line modeling, many effective methods have been proposed by scholars at home and abroad. At present, the methods for solving transmission line equations mainly include finite difference time domain method,
chain parameter matrix method, Green’s function method and BLT super-matrix equation method and so on. According to the BLT super-matrix equation theory of transmission line modeling, the synthetic voltage wave propagating along the pipeline on the wire is expressed as [25]

\[ W_i(x)_q = V_i(x) + qZ_c I_i(x) \]  
\[ V_i(x) = \frac{1}{2} \left( (W_i(x))_+ + (W_i(x))_- \right) \]  
\[ I_i(x) = \frac{1}{2Z_c} \left( (W_i(x))_+ - (W_i(x))_- \right) \]

where, \( q = \pm 1 \) represents the direction of voltage wave. ‘+’ represents forward traveling wave, and ‘−’ represents backward traveling wave.

FIGURE 1. Synthetic wave diagram.

The difference equation of the synthesized wave is

\[ \frac{d}{dx} (W_i(x))_q + q\gamma_i (W_i(x))_q = \left( W_i^S(x) \right)_q \]  

where, \( \gamma_i \) is the propagation constant of the wire. \( (W_i^S(x))_q \) is the synthesized excitation of forward or backward traveling wave.

If the fault point is at \( x = x_0 \), the voltage wave at any point \( x \) is

\[ (W_i(x))_q = e^{-q\gamma_i(x-x_0)} \cdot W_i(x_0) + \int_{x_0}^{x} e^{-q\gamma_i(x-x')} \cdot \left( W_i^S(x') \right)_q \, dx' \]

Regard \( (W_i^S(x))_q \) as lumped excitation source, then (6) becomes

\[ (W_i(x))_q = e^{-q\gamma_i(x-x_0)} \cdot W_i(x_0) + \int_{x_0}^{x} e^{-q\gamma_i(x-x')} \cdot \left( W_i^S(x') \right)_q \, dx' \]

It can be seen that the phase of the voltage wave on the wire is determined by \( \gamma_i(x - x_0) \). The voltage wave propagation delay is only related to position \( x \). In the same uniform medium, the fault phase and non-fault phase have similar \( \gamma \). There is the same amount of phase shift \( \gamma_i(x-x_0) \) between line-coupling voltage and current waves and fault voltage and current waves. It can be seen that these two have the same transfer function.

The expression of excitation source generated by line coupling is

\[ \left( W_i^S(x) \right)_q = e_i(x) + qZ_c h_i(x) \]

where, \( e_i(x) \) and \( h_i(x) \) are the distributed voltage source and current source generated by coupling, which are expressed as

\[ e_i(x) = - \sum_{j=1, j \neq i}^{N} Z_{ij} I_j(x) \]

\[ h_i(x) = - \sum_{j=1, j \neq i}^{N} Y_{ij} V_j(x) \]

where, \( Z_{ij} \) and \( Y_{ij} \) represent the mutual impedance and mutual admittance between wire \( i \) and wire \( j \) respectively.

Therefore, the coupling wave can also transfer distance information. So when the fault phase is unknown, the coupling signal of the non-fault phase can be used to locate the fault.

According to the electromagnetic topology theory, the reversal model can be treated as a three-conductor transmission line excited by a lumped source. It consists of three nodes and two wires, and the topology structure is shown in Fig. 2. J1 and J3 represent line terminals, J2 represents fault points. Three-conductor in the pipeline respectively represent A-phase, B-phase and C-phase. The voltage and current on each node are expressed by BLT super-matrix equation in the frequency domain as [26]

\[ [V] = \frac{1}{2} ([S] + ([T]) ([I] - [S][\Gamma])^{-1} [W^S] \]

\[ [I] = \frac{1}{2} [Y_C] ([S] - [T]) ([I] - [S][\Gamma])^{-1} [W^S] \]

where, \( Y_C \) represents characteristic admittance matrix of the transmission line. \( S \) represents the scattering hypermatrix. \( \Gamma \) represents the propagation hypermatrix. \( T \) represents correlation matrix of the pipeline. \( W^S \) represents the excitation source supervector.

In the reversal process, the three-phase currents measured at the head end are reversed and injected from the head end as a lumped excitation source. When the fault phase is unknown, according to the previous analysis, the fault phase can be assumed. It will not affect the accuracy of the positioning results even if it isn’t a real fault phase.

C. POSITIONING CRITERION OF IMPROVED EMTR ALGORITHM

When a fault occurs in the system, the fault state can be equivalent to the superposition of the normal operation state of the system and the additional state of the fault. The forward
propagation process of the fault transient traveling wave in the additional state is shown in Fig 3(a). \( Z \) is the total length of the line. \( Z' \) and \( Y' \) are the per-unit-length impedance and admittance of the line. \( Z_1 = \sqrt{Z'/Y'} \) is the wave impedance of the line. Then, the equivalent impedance at both ends of the line are set as \( Z_1 \) and \( Z_2 \). Assuming a fault occurs at \( x_f \), the voltage to ground at the fault point is \( U_f \), and the fault impedance is \( Z_f \).

![FIGURE 2. Electromagnetic topology diagram of three-phase transmission line.](image)

Similarly, it can draw a conclusion that the transient traveling waves of the fault phase and non-fault phase have the same amount of phase shift from part B of section II. When the system fails, the analytical solution of the voltage of the non-fault phase at \( x = 0 \) and \( x = l \) is

\[
U_{B1}(\omega) = \frac{1}{2} \left( 1 + \rho_1 e^{-\gamma_f x_f} \right) \frac{1 - \rho_f}{1 - \rho_f e^{-2\gamma_f x_f}} U_f(\omega) \\
U_{B2}(\omega) = \frac{1}{2} \left( 1 + \rho_2 e^{-\gamma_f (l-x_f)} \right) \frac{1 - \rho_f}{1 - \rho_f e^{-2\gamma_f (l-x_f)}} U_f(\omega)
\]

where, \( U_f \) is the coupling voltage between the fault phase to non-fault phase, its expression is

\[
U_f = \frac{Z_m - Z_C}{(Z_m + Z_C)} Z_C Z_0 / (Z_C + Z_0) \text{ is the node impedance.}
\]

After obtaining the time domain signal of voltage at the fault point, the frequency domain complex conjugate is used to realize signal reversal, namely

\[
U(x, -t) \rightarrow U^*(x, \omega)
\]

It can be seen that the number of observation points does not affect the location result of EMTR [11]. Considering that the double-terminal method has a high requirement for clock synchronization accuracy, the fault current obtained from a single observation point is used to locate the fault location in this paper.

According to Norton equivalent circuit principle, after electromagnetic time reversal, the frequency domain current of non-fault phase flowing through the left end of the line becomes

\[
I_{B1}(\omega) = \frac{U_{B1}^*}{Z_1}
\]

As shown in Fig 3(b), the reversal current is re-injected into the system from the left side of the line as a current source. Assuming that the fault point is located at the point \( x_g \), the current at this point is

\[
I_g(x_g, \omega) = \frac{1 + \rho_1 e^{-\gamma x_g}}{1 + \rho_1 e^{-2\gamma x_g}} I_{B1}(\omega)
\]

Introducing (14) and (17) into (18), we obtain

\[
I_g(x_g, \omega) = \frac{1}{2} \frac{(1 - \rho_f) (1 + \rho_1)^2 e^{-\gamma x_g}}{Z_1 (1 + \rho_1 e^{-2\gamma x_g}) (1 - \rho_f e^{+2\gamma x_g})}
\]

It is assumed that there are several guessed fault points \( x_f \) on the line. From (19), it can be known that the current energy of guessed fault point \( x_f \) reaches the maximum when \( x_f = x_g \). Since the 2-norm maximizes the energy square root, the 2-norm maximum criterion can be used as a criterion for fault location. The 2-norm of the current in frequency spectrum \([\omega_1, \omega_2]\) can be expressed as

\[
\| i_{x_g,\omega} (\omega) \|_{\omega_1,\omega_2}^2 = \left( \int_{\omega_1}^{\omega_2} i_{x_g,\omega}^2 (\omega) d\omega \right)^{1/2}
\]
where, $i_{xg,m}(j\omega)$ indicates the frequency domain value of short-circuit current at the guessed fault point.

Then, the 2-norm maximum criterion is expressed as

$$x_{f,real} = \arg \max_{x_g} \| i_{xg,m}(j\omega) \|_{\infty, \omega_1, \omega_2}$$  \hspace{1cm} (21)

where, $\arg \max_{x_g}$ represents the value of independent variable $x_g$ corresponding to the maximum value.

The time reversal method can locate the fault point mainly because the fault signal will achieve energy focusing at the target position. In the theory, then, the norms which characterize the amplitude or energy can be used as the criterion. We have compared the positioning results of the infinite norm and the 2-norm and found that results using the 2-norm are more accurate. The main reason is that the infinite norm corresponds to the peak value, and the 2-norm corresponds to the energy. So the 2-norm is adopted as the criterion.

D. IMPROVED EMTR ALGORITHM BASED ON COUPLING CURRENT

From above analysis, the fault location process of the improved EMTR algorithm based on coupling current is shown in Fig. 4.

1) After the line fails, we can record the transient fault current signal at the observation point on the left or right side of the line.

2) The frequency domain model of the reversal stage is built based on the BLT super-matrix equation, which uses the parameters and topological structure of the transmission line. According to the relevant knowledge of relay protection, the number of fault phases can be judged by the sudden changes of the interphase current and sequence components. The fault phase setting methods are as follows: Fault phase of single-phase-to-ground fault is assumed as A-phase. Double-phase-to-phase fault and double-phase-to-ground fault are setting as phase AB. Three-phase fault is set as ABC three-phase.

3) The calculated distance interval can be determined by the positioning accuracy requirements. For a line with the length of $L = 200km$, we assume a set of guessed fault locations $x_{g,m} (m = 1, 2, \ldots, L)$ with an interval of $\Delta L = 1km$.

4) The transient signal of single observation point is reversed and acted on this point as a lumped current source. The current response of the hypothetical fault phase at the guessed fault point can be calculated according to (10).

5) The 2-norm of current response is calculated according to (20). The guessed fault location with the largest 2-norm value is the fault location result.

III. ALGORITHM VERIFICATION

A. SIMULATION MODEL AND PARAMETERS

In order to verify the effectiveness of the improved EMTR algorithm based on coupling current, this paper uses ATP-EMTP to build a 750kV unbalanced transposed overhead transmission line with a total length of 200 km. Its schematic diagram is shown in Fig. 5.

At 50Hz, the power supply voltage of the M terminal and N terminal are $U_M = 780\angle 0^\circ$ kV and $U_N = 750\angle -35^\circ$ kV. The system impedance of each phase on the M and N ends are $Z_M = 3.18 + j111.21\Omega$ and $Z_N = 4.97 + j93.61\Omega$. Two sets of shunt reactors are connected on both sides of the line, and their reactance and resistance of each phase are respectively $4.116\Omega$ and $3\Omega$. The overhead line is an...
FIGURE 6. Results of fault location according to different phrase currents.
unbalanced transposed line. The per-unit-length impedance and admittance can be calculated using the LCC element in ATP-EMTP. Results are shown as follows \( Z \) and \( Y \), as shown at the bottom of the page.

It is setting the simulation time to 0.5s, assuming the line fault occurs at 0.2s, and sampling frequency is 1MHz. The data of the three-phase current are recorded at the M terminal from 0.2 to 0.21s.

Assuming that C-phase-to-ground fault (CGF) occurs at 160 km from the M terminal and the transition resistance is 10Ω. When the actual fault phase is unknown, the fault phase in the reversal modeling process can be assumed as A-phase, B-phase and C-phase respectively. Assuming a fault point every 1 km on the line, and then we can calculate the currents of these points in the reversal process according to (10). The 2-norm of hypothetical fault phase current at each guessed fault points can be calculated by using (20). The results obtained are shown in Fig. 6(a-c).

Similarly, when BC-phase-to-phase fault (BCF) and BC-phase-to-ground fault ((BCGF)) occur at 160 km away from M end, the normalized 2-norm results according to the different phase currents in the inversion stage are shown in Fig. 6 (d-i), respectively. As can be seen from Figure 6(a-i), although the specific fault phase is not known, the fault point can be accurately located according to any phase current. Therefore, even if the faulty phase is assumed to the non-faulty phase in inversion model, the fault location can be determined according to the current of the assumed faulty phase. So it solves the problem that the fault phase is unknown when the actual fault occurs. This paper uses the example for the parameters of the uniform lines.

**B. IMPACT OF FAULT TYPE ON LOCATION RESULTS**

Simulation of different fault types are carried out on the model shown in Fig. 4, and a guessed fault point is set every 100 m. The fault location results of the traditional algorithm and the improved EMTR algorithm are shown in Fig. 7. In improved EMTR algorithm, the CGF refers to C-phase-to-ground fault, and the fault phase is assumed to be A-phase in the reversal model. BCF represents the BC-phase-to-phase fault, BCGF represents the BC-phase-to-ground fault, and the reversal model assumes that the fault phases are A and B phase. ABCF represents three-phase short circuit fault, and the fault phases are assumed to be A, B, and C phase in the reversal model.

The traditional EMTR algorithm requires that the fault phases must to be known in the reversal modeling process. However, the improved algorithm can assume certain phase to be the fault phase when fault phase is unknown in the reversal modeling process. It can use the coupling current of the assumed fault phase to locate the fault point. The results of fault location based on the improved EMTR algorithm and the traditional EMTR algorithm are shown in Figure 7. Even if the faults of different types occur at different locations, the location results of the improved algorithm are as good as traditional EMTR method. The error rates of improved algorithm are not higher than 0.4%, and the actual fault type is not needed to know in advance. In this way, the application conditions of the time reversal algorithm are loosened to some extent.

The decoupling method uses phase-mode transformation to decouple. After obtaining the 1-mode currents at the observation points at both ends, this method combines the 1-mode currents with the EMTR method for fault location. Assuming that the fault is 120km away from the M terminal, the location results of the decoupling method and the improved EMTR algorithm are shown in Table 1. “—” in Table 1 indicates the fault position cannot be located.

It can be seen that both methods can achieve fault location well for most fault types, but when the C-phase-to-ground fault occurs, the decoupling method cannot locate the fault point. The decoupling method usually uses the Karenbauer transformation to obtain a 1-modulus, and its expression is \( i_1 = (i_u - i_b)/3 \). According to the fault boundary conditions, when the C-phase-to-ground fault occurs, the 1-mode component is 0. Therefore, it cannot reflect this kind of fault. Using other phase-mode transformations also has the...
problem that a single modulus cannot reflect all fault types. The improved EMTR algorithm used in this paper does not require decoupling, and can be used for all fault types to solve the problems existing in the decoupling method.

**C. INFLUENCE OF PHASE ANGLE OF POWER SUPPLY ON LOCATION RESULTS**

Assuming that a C-phase-to-ground fault occurs in the system 160 km from the M terminal, the transition resistance is 10\(\Omega\). According to the proposed improved EMTR algorithm, it can set A-phase as fault phase in the reversal stage. The location results of power supplies on both sides at different phase angles are shown in Table 2. It can be seen that the differences of phase angles between two sides do not affect the positioning results of the improved EMTR algorithm. Its location error is merely 0.1%.

**D. INFLUENCE OF TRANSITION RESISTANCE ON LOCATION RESULTS**

For a C-phase-to-ground fault, the influence of the transition resistance on fault location is shown in Table 3. Here, it is assumed that A-phase-to-ground fault occurs in the reversal model. It can be seen that the value of transition resistance does not affect the location results of the improved EMTR algorithm.

In actual working conditions, the transition resistance changes dynamically. However, it can be regarded as a fixed resistance in a very small period, which does not affect the transfer function of the line. The dynamic transition resistance has no influence on the fault location result.

**IV. CONCLUSION**

Aiming at the problems that the fault types need to be known in advance and the decoupling signal cannot reflect all fault types when using EMTR for line fault location, an improved EMTR algorithm based on coupled current is proposed.

1) Based on the BLT super-matrix equation, the propagation law of transient traveling wave in fault phase and non-fault phase is analyzed. It shows that coupling current of non-true fault phase can be used to locate the fault point.

2) When the fault phase is unknown, the improved EMTR algorithm uses the BLT super-matrix equation to calculate the current of each guessed fault point of the assumed fault phase in the reversal model. The 2-norm maximum of the current will appear at the real fault point, so the 2-norm can be used as criteria for fault location.

3) Simulation and calculation results show that the algorithm is not affected by the initial phase angle and transition resistance value, and it can achieve good location effect under different fault types.

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