A Novel Fault Elements Location Algorithm Based on Wide Area Fault Recorder Data for HV Transmission System

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Abstract. After a large-scale grid failure, it is important for dispatchers to know the faulty components and causes and to develop the correct scheduling strategy. In this paper, a new fault diagnosis scheme is presented based on widely configured fault recorders. The proceeded algorithm using the wide-area recorder data to locate the fault components such as transmission lines, busbars and transformers. Different indicators are given for different components on the grid. A variety of criterion indexes are deduced for the transmission line using the distributed parameter model. The credibility of the judgment is improved by using multiple criteria. A search scheme based on the initial adjacency matrix is used to locate fault component on the grid. The fault area is defined according to the uploaded recorder data. The fault components are searched in the wide defined fault area according to the proposed scheme. The element with the greatest probability of failure is found. The three faulty elements simulation models based on PSCAD/EMDTC are established and studied, what’s more, the power system model is also established to test the algorithm. The simulation results verify the effectiveness of the proposed method.

1. Introduction
Large-scale transmission grid is the backbone of power systems, at the same time, transmission system failures are always inevitable. Thus, large power systems call for precise and effective fault diagnosis algorithms to improve the overall safety and reduce economic losses. To solve this problem, many methods of fault diagnosis, such as expert system [1]; Bayesian network [2]; Petri nets [3]; artificial neural networks (ANNs) [4]; optimization technology [5] are proposed. Most diagnosis algorithms are protection system information or switch information based [6]. But this kind of algorithm is not reliable. For example, a mismatch between expected and real switch action could result in false diagnosis result. To solve the reliability problem in [6], the method Using several agents corresponding to several methods cooperate to fulfill fault diagnosis is proposed [7], but how to
properly combine different methods and how these agents cooperate are unsolved issues. With the development of phasor measurement units (PMU), the fault diagnosis model based on PMU data has also been studied [8]. But high cost of the PMU limits the wide configuration and thence popularization of this algorithm.

In order to help the dispatchers to locate fault components quickly after power grid fault, a fault diagnosis scheme based on fault recorder data is proposed in this paper. The fault criteria index of transmission line, transformer and bus are proposed in section 2. Section 3 introduces the fault element search method based on the adjacency matrix. In section 4, We show the PSCAD/EMTDC simulation results demonstrate the correctness of the proposed method.

2. Fault recognition index for different elements

2.1. Fault criteria of transmission line

2.1.1. Ratio criterion. The fault criteria using the synchronized voltage and current samples at both ends of a transmission line to calculate the location of the fault is presented in this section. Considering a transmission line with a non-fault distribution parameter model. Then both voltage and current measured at a distance Dl km away from receiving end obey the partial differential equations:

\[
\begin{bmatrix}
    U_s \\
    I_s
\end{bmatrix} =
\begin{bmatrix}
    \cosh(\gamma Dl) & Z_c \sinh(\gamma Dl) \\
    \sinh(\gamma Dl) / Z_c & \cosh(\gamma Dl)
\end{bmatrix}
\begin{bmatrix}
    U_r \\
    I_r
\end{bmatrix}
\]

(1)

Where, \(\gamma\) is called propagation constant of the transmission line respectively.

Figure 1 shows the schematic diagram of transmission line with fault. When an internal fault occurs at the point F (Dl km away from sending end), voltage at F can be expressed as:

\[
\hat{V}_F = U_s \cosh(\gamma Dl) - I_s Z_c \sinh(\gamma Dl)
\]

(2)

\[
\hat{V}_F = U_s \cosh(\gamma(1-D)l) + I_s Z_c \sinh(\gamma(1-D)l)
\]

(3)

(2) and (3) represent the post-fault voltages at fault point expressed in terms of measured sending and receiving data pair (VS; IS) and (VR; IR), respectively. From (2) and (3), the following expressions can be derived:
$$V_i = V_i + I_i Z_i \sinh(\gamma DL) - V_i (\cosh(\gamma DL) - 1) +$$

$$I_i Z_i \sinh(\gamma(1-D)l) - Vr (\cosh(\gamma(1-D)l) - 1)$$

(4)

$$T \sinh(\gamma DL) - J \cosh(\gamma DL) = 0$$

(5)

T is the index of fault recognition. When the fault occurs external or no fault occurs, \( DL \) is zero, so the absolute value of T and J are zero. Since such measured components all satisfy the transmission line equation, the computed absolute values of T and J will all be held at zero before the occurrence of a fault. This result can be derived using mathematical formulas for T.

When internal fault occurs, \( \cosh(\gamma DL) \) and \( \sinh(\gamma DL) \) in equation (5) are non-zero values and so does the index T. Thus, the different index value before and after the fault can be used as criteria index of the fault detection of transmission line.

$$|T| = |V_s - V, \cosh(\gamma l) - I_r Z_c \sinh(\gamma l)|$$

(6)

In order to distinguish fault, the T index before and after the fault are both calculated and used \( \lambda \) as the fault discrimination index of transmission line. When internal fault occurs, the calculated value is very large. A threshold variant \( \lambda \) is introduced whose expression is shown in equation (7).

$$\lambda = \frac{T^{[1]}}{T^{[0]}}$$

(7)

When the calculated value is greater than the threshold value, the line is regarded as faulty component. It should be noted that no assumptions in the procedure of derivation for the fault detection/location index \( \lambda \) are made. Hence, the index \( \lambda \) is hardly affected by the variations of source impedance, load change, fault impedance, fault inception angle and fault type.

2.1.2. Phase criteria index. Consider of an equivalent positive sequence network of a faulted line shown in Figure 2. It will be shown that this network is enough to detect the location of the fault. While the parameters of the line are represented by the distributed parameter model. The following equations can be obtained:

$$I_{s1} = I_s - V^\times_s Y/\dot{z}$$

(8)

$$I_{r1} = I_r + V_r^\times Y/2$$

(9)

Fault direction P could be defined from equation (1) and (2) based on the current direction.

$$P = \left| \arg \left( I_s - V_s^\times Y/2 \right) / (I_r + V_r^\times Y/2) \right|$$

(10)

In theory, when a fault occurs in the internal area, the value of P is \( \pi \). And when there is no internal fault the value of P comes to zero. For internal fault cases, the absolute value of the rises to a certain value with a large slope in practice. For external fault or none-fault cases, the absolute value of the will fast decay to zero. For the sake of high reliability, we set a threshold incorporated with a counter limit to recognize the faulted zone.

2.1.3 Differential current criteria index. For a normally operating two-terminal transmission line, the sum of the current phasors at both ends is zero. However, when fault occurs, the result of post-fault double-ended current phasors will be equal to the fault current value. Therefore, differential current
can be calculated as a criterion for fault detection.

\[ I_{\phi} = |I_m + I_n| \]  \hspace{1cm} (11)

Where \( \phi \) represents current phase which can be a, b or c.

2.2. Fault indicators for transformer and bus

2.2.1. Fault indicator for transformer. Differential current protection is commonly used as a main protection of the standard and non-standard power transformers. The calculation of the differential current at both ends of the transformer is rapid and sensitive to internal fault of the transformer. Differential current is measured by adding the vector current entering and leaving the circuit. The differential current measuring principle (DCMP) reflects the kind of circuit it reflects. In this paper, the differential current is adopted as the fault detection index of power transformer.

For the ubiquitous YD11-type transformer, it is necessary to consider the phase shift of the voltage and current. The positive sequence voltage and current of the star connect side lag 30 degrees behind the phasors of the delta connect side respectively. So we can get the differential current index for phase shift transformer:

\[ I_{\phi} = e^{j\pi/6} I_{\phi} * + I_{\Delta \phi} \]  \hspace{1cm} (12)

2.2.2. Fault indicator for bus. Like transformers, each outgoing line’s current on the bus satisfies the KCL law. And in this paper, we also take the differential current as the fault detection criteria of bus:

\[ I_r = |I_1 + I_2 + \cdots + I_n| \]  \hspace{1cm} (13)

Where \( I_k \) represents the current of line \( k \) connected with the bus (\( k \) is 1, 2, 3…n).

3. Fault element search scheme

Regarding power grid as a graph \( G \) without directions, and graph theory is used to simplify the complex electric network. The bus is denoted as vertex (V(G)), and transformer and transmission line is denoted as edges(E(G)). The connection between two nodes is expressed as a function(f(G)). The topology of the power system can be described as \( G=(V(G), E(G), f(G)) \). The adjacency matrix \( A = \sum a_{ij} \) is used to show the connection of the graph. The elements (\( a_{ij} \)) of the matrix represent the connection between vertex i and j. If vertex i and vertex j are directly connected, then \( a_{ij} = 1 \), otherwise \( a_{ij} = 0 \). If \( a_{ij} \) is not zero, record the branch connected with the two vertexes.

When fault occurs, the fault area is firstly ascertained using data from fault recorder. Then the adjacency matrix of the faulty area \( A_{\text{fault}} \) is formed based on fault recorder’s location. According to adjacency matrix \( A_{\text{fault}} \), component searches are performed. The search starts with the boundary node of the adjacency matrix, ending with the faulty element or the last node, making sure that each component is checked.
4. Simulation analysis

4.1. Performance of line fault index. To examine the performance of the proposed index, a model of a double-ended power supply with the rated voltage of 500 kV and the line length of 360 km, which is established using the PSCAD/EMDTC simulator, is adopted to evaluate the performance of the proposed scheme. The sampling frequency is 5000 Hz. Single phase grounding fault (take phase a for example) is simulated in internal and external of the line separately, and figures as follows show the absolute value of various indicators before and after the fault. Besides, all of the indexes are calculated based on positive sequence parameters and the sampling frequency is 5000 Hz. Figure 3 shows the ratio and T index curves, and the radio index of the post-fault is far greater than the pre-fault obviously. The fault ratio indexes of internal and external fault which are represented by positive sequence are showed in Figure 4. We can see that the ratio indexes between pre-fault and post-fault are very different. So, the ratio indicator can be used to distinguish the faults inside and outside the zone. Like the ratio indicator, Figure 5 and Figure 6 show the performance of the P indicator in detecting faults and distinguishing external and internal faults respectively. The curves of the P indicator are compared in these figures prove that it has good performance in fault detection.

Figure 3. The behaviors of fault ratio index and T index under positive sequence for a-g fault

Figure 4. The behaviors of fault ratio index under positive sequence between internal and external fault

Figure 5. The behaviors of fault P index under positive sequence for a-g fault

Figure 6. The response curves of P index between internal and external fault

4.2 Fault component location. In order to test the performance of the fault locating algorithm in the power grid, the proposed method is applied to the IEEE 9-bus test system. Table 1 shows the results of various indicators after the fault occurs and gives the faulty components located. Simulation results show that the proposed algorithm can quickly search for faulty components and locate them.
Table 1. The results of fault components location in the 9-bus test system

| Fault component | Fault type | Ratio index | P index | Differential current | Result |
|-----------------|------------|-------------|---------|-----------------------|--------|
| Line 1          | AG         | 442.485     | 1.4745  | 2.5656                |        |
|                 | BC         | 860.824     | 2.4873  | 2.8031                |        |
|                 | BCG        | 1040.4      | 2.6067  | 3.0147                | Line 1 |
|                 | ABC        | 1606.5      | 2.7993  | 3.2396                |        |
| T3              | AG         | 1.9357      |         |                       | T3     |
| Bus 5           | AG         | 1.8952      |         |                       | Bus 5  |

5. Conclusion
A fault element location algorithm for power system based on wide area fault recorder data is presented in this paper. Different fault detection indicators of power grid components are proposed, and elements searching method is given, too. After the fault occurs, the fault area and components can be quickly identified, which plays an important role in the safe and stable operation of the power grid. Simulation cases also verifies the effectiveness of the algorithm.

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