A novel fault location scheme for power distribution system based on injection method and transient line voltage

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Abstract. This paper presents a novel fault location method by injecting travelling wave current. The new methodology is based on Time Difference Of Arrival(TDOA) measurement which is available measurements the injection point and the end node of main radial. In other words, TDOA is the maximum correlation time when the signal reflected wave crest of the injected and fault appear simultaneously. Then distance calculation is equal to the wave velocity multiplied by TDOA. Furthermore, in case of some transformers connected to the end of the feeder, it’s necessary to combine with the transient voltage comparison of amplitude. Finally, in order to verify the effectiveness of this method, several simulations have been undertaken by using MATLAB/SIMULINK software packages. The proposed fault location is useful to short the positioning time in the premise of ensuring the accuracy, besides the error is 5.1% and 13.7%.

1. Introduction

The service continuity is one of the most important concerns to the medium-voltage distribution network, but faults are inevitable and often conducive to a power interruption. In order to fast recovery power supply, several fault location strategies have been proposed, such as Signal injection method [1-2], Travelling wave method [3-6], Zero-sequence Current Mutation method [7], Impedance [8], Transient Reactive Power Direction method [9-10], Transient Zero-mode Current Waveform Similarity method [11]. In the last years, several schemes have been proposed for travelling wave based on fault locators and put forward an equation that allows finding the fault. However, these methods are all of lack of automation. With the distribution power systems are more automated nowadays, then include additional voltage and current measurements along the network [12]. At present, there are many mentioned literatures on fault location have automation equipment installed in distribution systems. YANG Tuo-yuan et al. [13] presents a scheme for single-phase grounding of overhead line based on line-mode travelling wave mutation in power distribution system, that recommends the system to be installed the clock synchronization, it’s unable to distinguish trunk or branch. The injection method is widely used for its advantages of simplicity, clarity and high positioning accuracy [14-15]. As a consequence, in order to research more accurate fault located method, some strategies should be developed to exploit inject additional data.

According to the previously studied, this paper presents a fault location in distribution power systems based on injection method and transient line voltage method, considering the current reflected wave and transient line voltage at the main radial and feeder.
2. Proposed methodology
In this section, there will ignore the influence of distributed capacitance and electromagnetic coupling, basic principles of the paper will be reviewed. The injecting travelling wave methods and transient line mode voltage are the basics of fault locating principle for introducing the proposed methods. The main reasons for choosing injection current travelling wave in this research are that they are generally much less distorted than voltage [16]. The measurements at the main line and branch obtained at the end node have to be synchronized to assure the accuracy of the method.

2.1. Injection frequency
Taking into account the unbalanced nature of the power distribution. It’s necessary to convert the asymmetrical phase to symmetrical using the Karrenbauer Transform(KT) [17-18]. KT is defined as the transient modulus is converted to symmetrical components as show in the equation (1) in case of single-phase fault.

\[
\begin{bmatrix}
i_2 \\
i_1 \\
i_0
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & 0 & 0 \\
1 & -1 & 0 \\
1 & 1 & 1
\end{bmatrix} \begin{bmatrix}
i_0 \\
i_1 \\
i_2
\end{bmatrix}
\] (1)

Where \(i_0=i_1=i_2=1\), there is no faults. The system will come into being line-mode current when a single phase to earth happened.

Considering a radial distribution network for the proposed method is described as shown in Figure 1 which use the injection current to location . Equations for this method are derived assuming that the overhead line inject only line-mode currents into the system under load conditions. Injection technique starts from supposing a single-phase fault at the line section between node A1 and A3, the main line of the F point failure, the value of unit capacitance is \(C_0\), \(A_1A_2=L\), \(A_2A_4=L\), \(A_2F=L\), \(A_2A_4=L\), each branch admittance is \(j\omega L_3C_0\), \((j\omega L_1C_0+1)/R\) and \(j\omega L_2C_0\), setting the injection current into a unit[19-20]. Figure 1 shows the path of the injected signal.

![Image](image-url)

Figure 1. Signal current path for trunk fault failure.

Main line and branch current can be written as follows:

\[
I_{A1F} = \frac{(1 + j\omega R_0C_0L)}{(1 + j\omega R_0C_0L)}
\] (2)

\[
I_{A2A4} = \frac{j\omega R_0C_0L_2}{(1 + j\omega R_0C_0L)}
\] (3)

Therefore the current amplitude ratio of the branch can be written as:

\[
S_1 = \frac{1 + j\omega R_0C_0L_1}{j\omega R_0C_0L_2} = \frac{L_1}{L_2 + \frac{1}{j\omega R_0C_0L_2}}
\] (4)

Summary from equation (4) obtained as presented:

- If \(L_1/L_2>1\), first locating fault in the trunk, relatively, whether the calculation length is equal to the actual the actual and calculating length of the line;
- If \(L_1/L_2 \leq 1\), the fault location failure;
- \(S_1\) is inversely proportional to the injected signal \(\omega\), the signal frequency is too large lead to \(S_1<1\), that will increase the difficulty of judging fault branch.

As seen, this paper select injection signal frequency is 60 Hz instead of 50 Hz.
2.2. Fault-location scheme

2.2.1. Branch location

There is a single-phase fault at the line section between node A and B as shown in Figure 2. The positive direction of the current is the bus direction. In this method, the line mode impedance between node M and B is given by equation (5). Its reflection and refraction of the injected current at the M point as presented in equation (6) and equation (7).

\[ Z_{oe} = \sum_{i=1}^{N} Z_{xi} \]  

(5)

\[ i_{Rs} = \frac{Z_{Ne} - Z_{xe}}{Z_{Ne} + Z_{xe}} \cdot i_i \]  

(6)

\[ i_{Rs} = -\frac{2Z_{Ne}}{Z_{Ne} + Z_{xe}} \cdot i_i \]  

(7)

Figure 2. AB&AD fault injection reflection wave.

Where N is the number of nodes. These reflected electromagnetic waves diffuse away from the fault point at speeds close to the light. Assuming all line parameters are the same. The measurement M is only able to detect the fault reflected waves before F.

Figure 2(a) shows AB failure, S_A is the jointly reflected wave of the trunk. The path of injection line-mode reflected wave S_D is F→A→D→M while AB failure grounding, S_D is slower 2AD/v than the initial wave crest arrival to point M. Figure 2(b) shows the path of injection line-mode reflected wave S_DB is F→A→B→M during AD fault, its slower 2AB/v than the initial wave crest.

Figure 3. BC&BE fault injection reflection wave.

Similarly, Figure 3 displays the equivalent path of injection line-mode reflected wave and the common reflected wave is SA. The travelling wave propagation path is FhA→D→h during BC fault, expressed in S_D, its time difference is 2AB/v. The journey of injection reflected wave is F→B→C→M when the fault point F in BE segment, which receive time of reflected wave peak deviate by 2BC/v, the schematic diagram as shown in Figure 3(b). In this method, at the measurement M, the location of branch can be determined by comparing the arrival times of the first travelling-wave signal peaks, fault distance functions are as follows:

\[ \begin{align*}
\text{Trunk line:} & \Delta t = 2q/v \\
\text{Branch:} & \Delta t = 2k/v
\end{align*} \]  

(8)

Where \( \Delta t \) is the Time Difference Of Arrival(TDOA), \( q \) is twice extent of previous branch length, \( k \) is main line length after fault point. \( v \) is wave velocity, \( v=3*10^8\text{m/s} \) [19].As the result of the above
analysis of the Figure 2 and Figure 3. When trunk fails, the TDOA of reflected wave, which is equal to \( q \) divided by \( v \). When the branch fails, the TDOA of reflected wave is \( k \) divided by \( v \). Table 1 shows the results according to the Figure 2 fault location algorithm.

### Table 1. Reflected wave method responses (\( \mu s \)).

| TDOA | \( S_A \) | \( S_D \) | \( S_E \) | \( S_{DB} \) | \( S_{EC} \) |
|------|-----------|-----------|-----------|-----------|-----------|
| \( \Delta t \) (\( \mu s \)) | \( 2MA/v \) | \( 2AD/v \) | \( 2BE/v \) | \( 2AB/v \) | \( 2BC/v \) |

#### 2.2.2. Fault location

Figure 2(a) shows a trunk fault to ground simplified radial diagram. The proposed method will use the injection reflected wave between fault point and branch as shown in Figure 4. The path of \( S_{FA} \) comes from fault point is \( F\rightarrow A\rightarrow F \rightarrow D \rightarrow M \), \( S_{FD} \) as the reflected wave comes from D node, the path of \( S_{FB} \) is \( F\rightarrow A\rightarrow F \rightarrow D \rightarrow M \), equations describing their TDOA is:

\[
\Delta t_{AB} = 2AF/v = (0 - 2AB/v) \tag{9}
\]

\[
\Delta t_{AB} = 2(AD + AB)/v = [2AD/v - 2(AD + AB)/v] \tag{10}
\]

\[
\Delta t_{AB} = 2AB/v \tag{11}
\]

![Figure 4](image)

(a) AB failure  
(b) AD failure

**Figure 4.** AB and AD fault-related characteristic wave path.

Subtracting equation (11) from (10), it can be obtained

\[
\Delta t' = \Delta t_{AB} - 2AD/v = 2AF/v = (0 - 2AB/v) \tag{12}
\]

When a fault located in branch AD like Figure 2(b), relatively, the path of reflected injection signal \( S_{FA} \) is \( F\rightarrow A\rightarrow F \rightarrow M \), the route of \( S_{FB} \) is \( F\rightarrow A\rightarrow F \rightarrow B \rightarrow M \), \( S_{AB} \) as the reflected wave for the line section AB. TDOA of \( S_{FA} \), \( S_{FB} \) and \( S_{AB} \) is:

\[
\Delta t_{AB} = 2AF/v = (0 - 2AD/v) \tag{13}
\]

\[
\Delta t_{AB} = 2(AD + AB)/v = [2AB/v - 2(AD + AB)/v] \tag{14}
\]

\[
\Delta t_{AB} = 2AB/v \tag{15}
\]

By subtracting equation (15) from (14):

\[
\Delta t' = \Delta t_{AB} - 2AB/v = 2AF/v = (0 - 2AD/v) \tag{16}
\]

Therefore, \( \Delta t_{AB} = \Delta t' \) for main line fault; \( \Delta t_{AD} = \Delta t' \) for branch fault. Subsequently, the injection reflected wave Maximum Correlation Time(\( t_f \)) can be defined as peak appearance simultaneously between \( \Delta t_{AB} \) and \( \Delta t_{AD} \), fault distance MF function is defined as:

\[
MF = MA + v \cdot t_f / 2 \tag{17}
\]

### Table 2. Maximum correlation time and distance.

| Length(m) | MA | AB | AD | BC | BE |
|-----------|----|----|----|----|----|
| \( t_f \) | \( V \cdot t_f /2 \) | \( MA + v \cdot t_f /2 \) | \( MA + v \cdot t_f /2 \) | \( MB + v \cdot t_f /2 \) | \( MA + v \cdot t_f /2 \) |

It is obvious from above function (17) that the fault distance created as described in Table 2 with Figure 1 illustrate about the relationship between \( t_f \) of the injection signal reflected wave and fault length during different feeders of faults. As can be seen from the Table 2, the fault distance is the only calculated which uses the wave velocity multiplied by time in all types of faults. For this reason, in this study, \( t_f \) is employed to be detected and calculated the line length of faults.
As mentioned earlier, the proposed method adapts to many simplified distribution power system. Nevertheless, travelling wave will totally reflect in the end of feeder with Δ/Yn or Y/Yn transformers. In case a fault strikes within the end of transformers, take order to think out an appropriate method that having the ability to locate complicated and changeable medium-voltage distribution system. ZHANG Lin-li et al and Ma Shi-cong et al [16,17] put forward a new location approach based upon transient voltage measurements to solve interference of travelling-wave total reflection against different feeders faults. At the end of fault feeder, Table 3 shows amplitude comparison between one and another phase transient voltage for the proposed method.

### Table 3. Transient voltage amplitude comparison.

| Fault | Criterion |
|-------|-----------|
| Phase A | $U_{ab}(t)>U_{ac}(t)$&$U_{bc}(t)>U_{ba}(t)$ |
| Phase B | $U_{bc}(t)>U_{ab}(t)$&$U_{ab}(t)>U_{bc}(t)$ |
| Phase C | $U_{ac}(t)>U_{ab}(t)$&$U_{ba}(t)>U_{ac}(t)$ |

### 3. Simulation results

In order to validate the effectiveness of the proposed scheme, several simulations were performed using MATLAB/SIMULINK. The medium-voltage overhead line topology is shown in Figure 5. A is set as the signal inject point, the 10 kV/0.4 kV distribution transformers connect to each feeder terminal and the three-phase asymmetric load details as shown in literature [1]. The amplitude of the injected current signal is 100mA, duration is 4μs, ground resistance $R=100\Omega$. Additionally, the distribution network has some measurements at the injection and feeder terminals. A method is proposed to locate the fault by injecting 60Hz line-mode current and the transient line voltage. It’s proved that the injection frequency is 60Hz line-mode current can achieve the purpose of completely positioning the fault by theoretical.

![Figure 5. Low-voltage overhead line simulation topology diagram.](image)

The fault location accuracy of injection method base on travelling-wave method in LEI et al.[1] and literature [17-21]. The conclusion of previous studies show that the inject signal to locate fault accuracy is higher, in case the fault distance is less than 45km and the ground resistance is less than 10kΩ.

In this proposed fault location scheme result as shown in Table 4 and 5 for different branches fault. The wave recorders are installed at the end of the trunk and necessary branches. In the different branch location, the distances have been calculated according to the TDOA of injected current reflected travelling wave. Fault line cases are tested based on changing the primary branch as. Table 5 shows the results of fault location for primary branches fault.

The results have been represented in Table 4 and 5 verify that the reflected travelling-wave farther away, the higher the accuracy. The results of fault location demonstrate that with the increase of fault distance, the velocity error between the characteristic wave and reflected wave cause TDOA to be shorten. Therefore, when the length less than 50km and grounding resistance less than 10kΩ, the distance error will be less than 50m.
Table 4. Results of single-phase ground fault for trunk.

| t_f/μs | Actual t_f/μs | Calculated length/km | Actual distance /km | Trunk |
|--------|---------------|-----------------------|---------------------|-------|
| 14.5   | 3.3           | 2.175                 | 1                   | AB    |
| 19.3   | 10.7          | 2.895                 | 3.2                 | BC    |
| 44.3   | 23.3          | 6.645                 | 7                   | CD    |
| 105.8  | 53.3          | 15.870                | 16                  | DE    |
| 121.1  | 61.5          | 18.165                | 18.45               | EF    |

Table 5. Results of fault location for primary branch.

| t_f/μs | Actual t_f/μs | Calculated length/km | Actual distance /km | Branch |
|--------|---------------|-----------------------|---------------------|--------|
| 51.8   | 20.0          | 7.77                  | 7.2                 | CG     |
| 126.7  | 43.3          | 19.005                | 19                  | DI     |
| 124.6  | 43.3          | 18.69                 | 19.1                | IH     |
| 124.8  | 60.0          | 18.72                 | 19                  | EK     |
| 122.5  | 60.0          | 18.375                | 18.5                | EM     |

As discussed in section 2.1, when the single-phase fault occurs at the point A, Figure 6 shows obtained as the result of a fault location error to A in different frequencies. Before analyzing the results, the actual velocity difference in the line of travelling-wave is inevitable, considering the line fixed error and sampling frequency. In case \(|f| \leq 2 \mu s\) \((|\Delta| \leq 300\mu m)\), the TDOA of 2.0μs is theoretically feasible under the sampling condition of 0.1μs.

Figure 7-8 shows the A-phase to ground fault simulation result of CD and DI. The TDOA that measurement A detect is respectively 44.3μs and 46.3μs. Using equation (17) to calculate the length is 6645m and 12945m respectively the simulation results verify the effectiveness of the proposed method, besides the error is 5.1% and 13.7% relative to the actual line length. The DI branch error is large makes mis-judgment from the result, so the injection travelling-wave total reflection when inject signal arrive at the end of DI.

Figure 6. Error for different frequencies.

Figure 7. CD fault peak time waveform.

Figure 8. DI fault peak time waveform.

Figure 9. H terminal transient waveform.

The calculated and actual length of DI, IH, IJ and EK are almost equal which demonstrates that the TDOA little age difference from table 5, there will be pseudo fault points. Figure 9 shows the transient voltage and current that can be detected to location IJ fault branch. It can be seen that the end of transform transient line voltage is \(U_{ab}>U_{ca}\) and \(U_{ca}>U_{bc}\). Therefore fault location IJ branch.
4. Conclusions
This here presented an approach is based upon the travelling-wave refraction and reflection along the distribution line, take advantage of actual automated instrument. The fault distance were calculated and the results were reported. The injection frequency simulation result is 60 Hz and it verified that the error percentage has been decreased. Then according to multiple branches simulation, a proposed fault location scheme illustrated that using the TDOA of reflected travelling-wave peak arrival time at the end node of main feeder could improve the accuracy. Furthermore, an approach ,which is obtained through comparison of transient voltage amplitude at the end of transformer distribution line, can offset the influence of total reflection. Finally, the proposed methodology can not only eliminate the influence of unbalanced load, but also save synchronous clock for unnecessary line on the distribution network, reducing the cost of distribution line, shorten the time of power recovery.

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