A Novel Method for Single Phase-to-Ground Fault Location Based on Wavelet Analysis and Correlation

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***Abstract*—This paper deals with the problem of single phase-to-ground fault location in distribution networks. A novel method is proposed that overcomes the difficulties that traditional fault location methods have, like their sensibility to the large transition resistance due to the fault. First, correlation is used in combination with the wavelet transform to analyze the series of transient electric wavefronts generated by the fault. Then, the travelling wave principle is applied to determine the distance between the busbar and the fault location. Theory analysis and ATP simulation indicate that the proposed method is robust and accurate.**

***Index Terms*—Distribution network, Wavelet transform, Correlation, Travelling wave, Fault location**

I. Introduction

Single phase-to-ground fault occurs with the highest probability in distribution systems, accounting for 80% of all failures. Due to the fault's large transition resistance, and the many bifurcations in the distribution network, the traditional fault location methods cannot get the correct location.

When the failure occurs, fault location and line protection should be achieved as quickly as possible to ensure that the system can operate safely and guarantee power quality. However, the fault is in fact allowed to continue running for 1-2 hours but not longer. Otherwise, more complex faults could occur, due to the feeder lines having large capacitive current and fault arc instability [1].

The single-terminal fault location methods are widely used in the distribution network, which commonly adopts the radial topology. Among these, the method used most often is the impedance method, which is easy to implement and reliable. In this method, the impedance of the power line is obtained through the voltage and current of the busbar. Then, the fault location is obtained by using the relationship between the impedance and the line length. But the drawback of this method is that its accuracy is easily affected by the value of the transition resistance, the operation mode of the distribution network, and the accuracy of CT and PT [2].

Another method is to install remote terminal units (RTU) in different segments of the power line. But given that several RTUs need to be installed in each feeder, this method does soar the cost of the protection. Moreover, there is the possibility that communication would fail, with wrong or no information being shared, with the result of unwanted or failed tripping. These two negative points lead to difficulties in the method being applied widely [2]–[4].

Over the past decade, with the decreasing cost of micro processors and high-speed sampling units, as well as the development of digital signal processing, the traveling wave extraction and the use of traveling-wave methods has made great progress [5].

The type A single-ended modern travelling-wave principle identifies the voltage or current transient components produced by the fault, and then calculates the fault location by using the time differences between arrivals of generated wavefronts at the measure point. The type C modern travelling-wave principle injects a high frequency signal instead of using the disturbance wave caused by the fault itself, to calculate the fault location using the same mecanism as in type A [6], [7].

Using the type A single-ended modern travelling-wave principle as the basic fault location method, this paper presents a variant based on correlation analysis of wavelet transforms. Classical correlation detects a linear relationship in the frequency domain between two signals, while wavelet transform based correlation detects such similarities by taking into account both the time and the frequency domains, being a superior method [8]–[10].

The ATP simulation ilustrates the high accuracy of the proposed method, and also demonstrates that it is not affected by the value of the ground transition resistance.

II. The model

A. The line model

When a fault occurs, there is a coupling between the phases, which can be overcomed by using the Karrenbauer transformation or the Clarke transformation. Calculations are also performed faster by using such model.

B. Traveling wave in the distribution network

When a fault occurs, the fault point generates a travelling wave that propagates along the power line. The wavefront can refract and reflect at an impedance discontinuity point. In the distribution network, these points could be the fault point, a branch point, the busbar point, and the end of the power line.

In Fig. 1, a single phase-to-ground fault occurs in point F. The generated travelling wave propagates in both direction senses of the power line. When the travelling-wave reaches the impedance discontinuity point O, a reflection wave propagates back, and a refraction wave propagats forth, reaches the busbar point M, and reflects again. These reflections and refractions continue until the transient signal disappears, so the measure point M will detect many wavefronts.

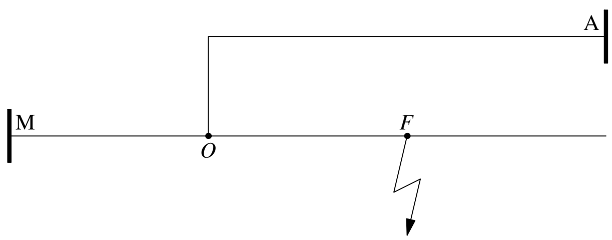

Fig. 1. The principle of travelling wave in bifurcation line

C. The principle of fault location

Let t_1 be the time of the zero sequence components wavefront arriving at point M through the path:

$$F \to O \to M$$

And let t_2 be the time corresponding to the path:

$$F \to O \to M \to O \to F \to O \to M$$

Then, if v is the propagation speed of the current waves in the power line, the fault location is L_{MF}:

$$L_{MF} = v\frac{t_2 - t_1}{2} \tag{1}$$

D. The wavelet transform

The travelling wave caused by the line fault is a non-stationary, non-smooth, singular in both time and frequency domains, high frequency signal.

Because the more notable characteristic of the wavelet transform is its good capabilities for time-frequency localization, it is a good tool to analyze singular signals like in this case [11].

Let the travelling wave signal (current's voltage) be $f(t)$, and let the mother wavelet be $\Psi(t)$. Then the wavelet transform is

$$WT(a\tau) = \int f(t)\Psi_{a\tau}(t)dt \tag{2}$$

while

$$\Psi_{a\tau}(t) = \frac{1}{\sqrt{a}}\Psi\left(\frac{t-\tau}{a}\right) \tag{3}$$

is the scale displacement and stretching of the mother wavelet.

When $a = 2k,\ k \in \mathbb{Z}$, this transform is known as the binary wavelet transform.

In this paper, the cubic spline function is used as mother wavelet.

E. The principle of correlation

The correlation is a measure of the similarity between two waveforms $x(t)$ and $y(t)$ as a function of a time-lag τ applied to one of them. Let the mean squared error D between both signals describe the similarity of the two signals in the time domain:

$$D = \frac{1}{T}\int_0^T \delta^2 dt \tag{4}$$

where

$$\delta = x(t) - \alpha y(t+\tau) \tag{5}$$

and α is a parameter.

The value of α that minimizes D is calculated by solving $\frac{\delta D}{\delta \alpha} = 0$. D_{min} is as follows:

$$D_{min} = \frac{1}{T}\int_0^T x^2(t)dt\left(1 - \rho_{xy}^2(\tau)\right) \tag{6}$$

where

$$\begin{aligned}\rho_{xy}(\tau) &= \frac{\frac{1}{T}\int_0^T x(t)y(t+\tau)dt}{\sqrt{\frac{1}{T}\int_0^T x^2(t)dt}\sqrt{\frac{1}{T}\int_0^T y^2(t+\tau)dt}} \\ &= \frac{R_{xy}(\tau)}{\sqrt{R_{xx}(0)}\sqrt{R_{yy}(\tau)}}\end{aligned} \tag{7}$$

with

$$0 \le \rho_{xy} \le 1 \tag{8}$$

Clearly, the bigger ρ is, the smaller D is, and the two signals are more similar. If $\rho = 1$ and $D = 0$, $x(t)$ and $y(t+\tau)$ are identical.

If the signals are sampled, the equivalents of eqs. (6) and (7) are:

$$D_{min} = \frac{1}{N}\sum_{n=0}^{N-1} x^2(n)\left(1 - \rho_{xy}^2(k)\right) \tag{9}$$

$$\begin{aligned}&\rho_{xy}(k) = \\ &= \sum_{n=0}^{N-1} x(n)y(n+k)\left(\sum_{n=0}^{N-1} x^2(n)\sum_{n=0}^{N-1} y^2(n+k)\right)^{\frac{1}{2}}\end{aligned} \tag{10}$$

F. The calculation of the fault location

In Fig. 2, F is the single phase-to-ground fault point. The fault ocurring is considered as instantaneous, and therefore the operation mode is assumed to be not changed, and the equivalent resistance and the propagation speed of the travelling wave to remain the same.

First, the transient current, as detected in measure point M, is processed by using the wavelet transform. The singular peaks representing the arrivals of the successive wavefronts are found. The first peak, representing the first arriving wavefront, is compared with the following ones through correlation analysis. The peak found most similar to the first one shall correspond to the wave travelling along the fault line between measure point M and fault point F. This is so due to the fact that the transition resistance is usually pure resistance, and as a consequence produces no distortion to the wave, it only

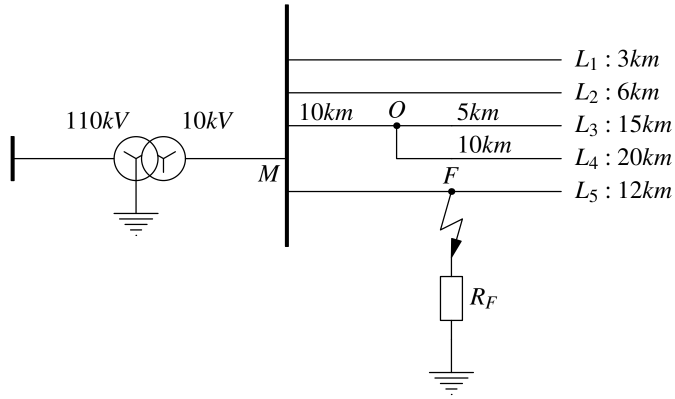

Fig. 2. The model of simulation system

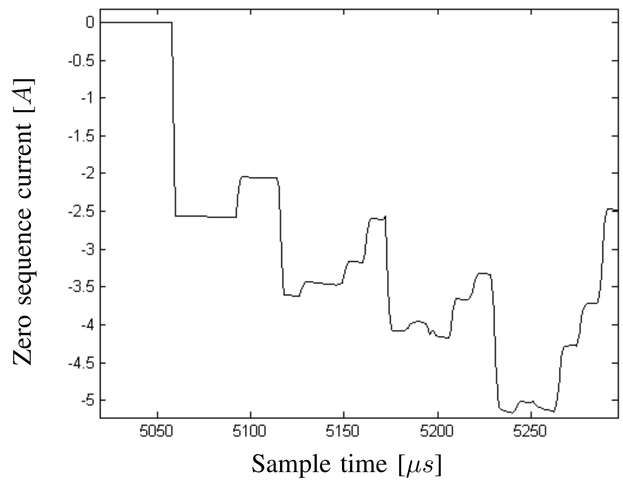

Fig. 3. Single phase-to-ground fault transient current

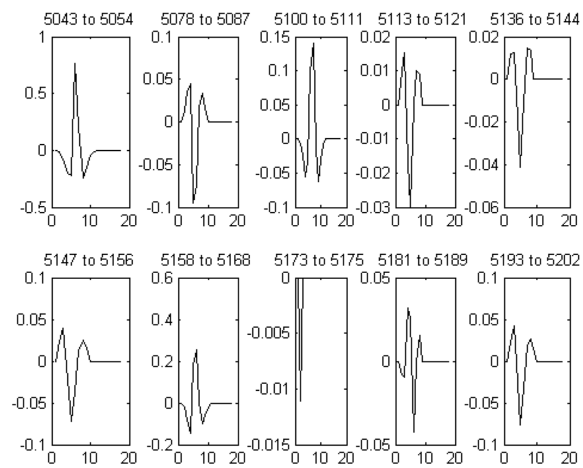

Fig. 4. Wavelet transform of the the transient current wavefronts

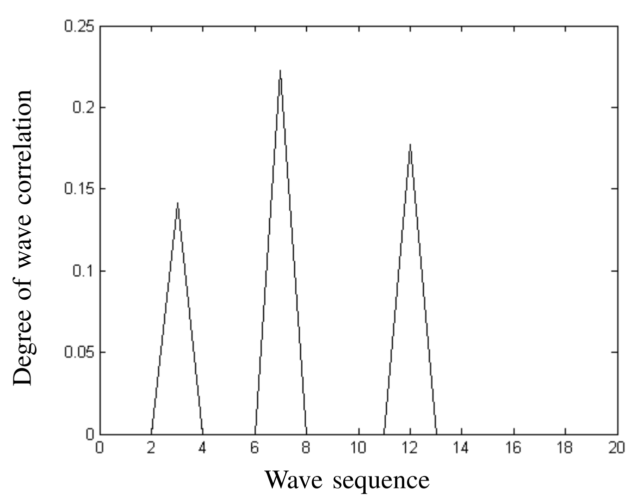

Fig. 5. Results of correlation

contributes to its attenuation, preserving the waveform. On the other hand, the waves propagating along other possible paths across the distribution network will be affected by distortion every time they are reflected or refracted at impedance discontinuity points. Attenuation is no problem, because at present, detection devices can deal with quite weak signals.

The time of arrival at measure point M of the first peak is set as zero time t_1. The time of arrival at M of the next most similar peak is t_2. Finally, the time difference between arrivals of both peaks is used to calculate the fault location through (1).

III. The simulation

The single phase-to-ground fault is simulated by ATP according to Fig. 2. The parameters are:

$$Z_0 = (0.23 + j\ 1.72)\ \frac{\Omega}{km},\ b_0 = j\ 1.884\ \frac{\mu S}{km}$$

The zero sequence component velocity is:

$$v_0 = 1.745\ 10^5\ \frac{km}{s}$$

The sample rate is $1MHz$. It is assumed that there is a fault in L_5 with an inception angle of $45°$ and a transition resistance of 1000Ω. Fig. 3 illustrates the transient current.

Fig. 3 indicates the first ten peaks, obtained through the wavelet transform, representing wavefront arrivals at M.

According to the correlation analysis, peak 7 in Fig. 3 is the most similar one to the peak 1, as shown in Fig. 5.

The time difference between both peaks is $(5158-5043)\mu s$. Fault location is gained through (1):

$$L = v_0\ \frac{5158 - 5043}{2}\ 10^{-6} = 10.034\ km$$

The error falls within $50m$, which ilustrates how this method presents improved accuracy over the traditional impedance method.

TABLE I shows the results of five more simulations, each with a different fault point along L_5, and with an inception angle of $45°$, and a transition resistance of 10Ω. The error falls within $100m$.

TABLE I
ESTIMATED FAULT LOCATION WITH AN INCEPTION ANGLE OF $45°$ AND A TRANSITION RESISTANCE OF 10Ω

Fault point $[km]$	2	4	6	8	10
Fault location $[km]$	2.094	3.926	6.020	7.940	10.034
Error $[km]$	0.094	-0.074	0.02	-0.06	0.034

TABLE II
ESTIMATED FAULT LOCATION WITH VARYING INCEPTION ANGLES AND TRANSITION RESISTANCES

	Transition resistance		
	0Ω	10Ω	100Ω
Inception angle	Fault location $[km]$ Error $[km]$		
$0°$	5.933 -0.067	6.020 0.02	6.020 0.02
$45°$	6.020 0.02	5.933 -0.067	6.020 0.02
$90°$	6.020 0.02	5.933 -0.067	6.020 0.02

TABLE III
ESTIMATED FAULT LOCATION WITH AN INCEPTION ANGLE OF $45°$ AND A TRANSITION RESISTANCE OF 100Ω

Fault line	L_1	L_2	L_3	L_4	L_5
Fault location $[km]$	2.967	3.054	2.967	3.054	3.054
Error $[km]$	-0.033	0.054	-0.033	0.054	0.054

TABLE II shows the results of nine more simulations, each with the same fault point at $6km$ in L_5, and with an inception angle of $0,\ 45,\ 90°$, and a transition resistance of $0,\ 10,\ 100\Omega$. It can be seen how the proposed method is not affected by the transition resistance or the inception angle, and the error always falls within $100m$.

Finally, TABLE III shows the results of yet five more simulations, each with the fault point at $3km$ in a different feeder line, and with an inception angle of $45°$, and a transition resistance of 100Ω.

IV. CONCLUSION

The simulation testifies the accuracy and robustness of the method for fault location. The accuracy obtained in the simulations falls within 100m. And it is shown how the method is not at all affected by the value of the transition resistance, as opposed to the impedance method, nor by the value of the inception angle.

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