

# An Improved Method for Fault Location based on Traveling Wave and Wavelet Transform in Overhead Transmission Lines

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## Abstract

An improved method for detecting fault distance in overhead transmission lines is described in this paper. Based on single-ended measurement, propagation theory of traveling waves together with the wavelet transform technique is used. In estimating fault location, a simple, but fundamental method using the time difference between the two consecutive peaks of transient signals is considered; however, a new method to enhance measurement sensitivity and its accuracy is sought. The algorithm is developed based on the lattice diagram for traveling waves. Representing both the ground mode and alpha mode of traveling waves, in a lattice diagram, several relationships to enhance recognition rate or estimation accuracy for fault location can be found. For various cases with fault types, fault locations, and fault inception angles, fault resistances are examined using the proposed algorithm on a typical transmission line configuration. As a result, it is shown that the proposed system can be used effectively to detect fault distance.

Key Words : Fault Location, Lattice Diagram, Modal Transformation, Overhead Transmission Line, Traveling Wave, Wavelet Transform

## 1. Introduction

Overhead transmission lines are exposed to the atmosphere for a long time and are complexly composed of various equipments and utilities.

Therefore, line faults may occur frequently, due to various reasons such as lightning, short circuits, faulty equipment, overload, and deterioration of conductor. Most electrical faults are evidenced by mechanical damages which must be repaired before the lines can be restored to normal service. Hence, restoration can be made in proper time only when the fault location can be correctly known or estimated with reasonable accuracy. In particular, most domestic transmission lines are installed in mountainous terrain, making it difficult to find the

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fault location or requiring a great deal of labor to repair it. Finally quick detection, isolating and repairing of such faults are critical in maintaining the power system operation efficiently and reliably [1].

Techniques of determining fault location can be typically classified into two main categories: one is based on impedance which is measuring phase voltages and line currents with a fundamental frequency, and the other is to use traveling wave theory for the transient signals which contain high-frequency components [2]. One of the greatest drawbacks for the impedance method is the low accuracy of at least 2~3[%] for the line length. In order to overcome this problem, the traveling wave technique has been introduced to locate faults. When a fault occurs, the voltage or current at the fault point suddenly changes. Such change produces a high-frequency electromagnetic impulse called the traveling wave or surge.

Fault location methods using traveling waves are independent of network configuration and devices installed in the network. In recent years, it has been more interested in fault location due to improvements in data acquisition and signal processing system, global positioning system for time synchronization and communication system [3]. Fundamental methods using traveling waves are single-ended and double-ended techniques. Despite the possibility of several difficulties, the single-ended method has been more interesting in fault detection because of well developed signal processing system in addition to economic reasons. Hence, it becomes very important to design both a sampling frequency and a time measurement algorithm for the single-ended monitoring system. A simple, but fundamental method using the time difference between two peaks of transient signals will be taken into consideration. In this experiment,

a new method is proposed to enhance estimation sensitivity and its accuracy. This algorithm is developed with reference to the lattice diagram, representing the two modes, ground mode and alpha mode, of the traveling wave. Several properties to increase recognition rate or accuracy of fault location will be discussed.

## 2. Fault Transmission Line

### 2.1 Fault and Modal Transformation

Consider a transmission line with its length,  $L$  connected between bus, A and B, as shown in Fig. 1. It is assumed that a fault occurs at a distance,  $L_x$  from the monitoring bus A. A's sudden change of signals due to fault generates transients with high-frequency disturbance, and it travels like a surge along the line in both directions and continues to bounce back and forth between the fault point. Hence, the monitored fault transients at the end of the line will contain abrupt changes at intervals, corresponding to the travel times of signals between the fault point and a monitoring point. Using the knowledge of the speed of traveling waves on the given line, the fault location can be determined easily. As surges reach any discontinuity on a transmission line, a portion of the traveling wave is reflected from and transmitted through the discontinuity point such as a fault point, circuit breaker, or bus. This phenomenon lasts until the traveling wave is settled to any other stable status.

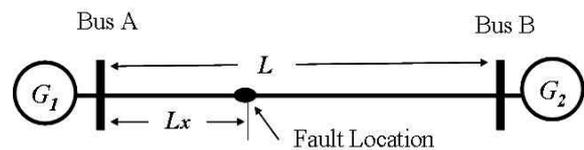


Fig. 1. Transmission line under study

Phase voltages and line currents propagate away from a fault point in both directions of the line at approximately the speed of light. In the lossless transmission line, the traveling voltage and current signals in the distance of  $x$  for the time of  $t$  can be represented as [4]

$$e(\mathbf{x}, t) = \mathbf{f}_1(\mathbf{x} - \mathbf{vt}) + \mathbf{f}_2(\mathbf{x} + \mathbf{vt}) \quad (1)$$

$$\mathbf{i}(\mathbf{x}, t) = \frac{1}{\mathbf{Z}_0} [\mathbf{f}_1(\mathbf{x} - \mathbf{vt}) - \mathbf{f}_2(\mathbf{x} + \mathbf{vt})] \quad (2)$$

where  $\mathbf{Z}_0 = \sqrt{\mathbf{L}/\mathbf{C}}$  and  $\mathbf{v} = 1/\sqrt{\mathbf{LC}}$  are characteristic impedance and wave speed, respectively, and  $\mathbf{f}_f$ ,  $\mathbf{f}_b$  are forward and backward waves.

On the other hand, three phase transmission lines are usually significantly electromagnetic coupled between conductors. The coupled signals are decomposed into a new set of signals by means of modal transformation. As a result, each of the modal components can be independently treated to a single phase signal. Three phase components can be transformed by

$$\mathbf{S}_m = \mathbf{T} \times \mathbf{S}_p \quad (3)$$

where  $\mathbf{S}_m = [s_g \ s_a \ s_b]^T$  and  $\mathbf{S}_p = [s_a \ s_b \ s_c]^T$  denote modal components and phase components, respectively, and  $\mathbf{T}$  is a transformation matrix. Assuming the line is well transposed, the phase components can be transformed by Clark's transformation matrix [2] with real elements as

$$\mathbf{T} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix} \quad (4)$$

In modal transformation components,  $s_g$  is defined as ground mode, or common mode. As aerial modes

or differential modes,  $s_a$  and  $s_b$  are called to alpha mode and beta mode, respectively.

Using the mode transformation matrix, phase components can be decomposed as a linear combination of three modal components. The ground mode signal shows higher amplitudes only which the fault current path is to the earth, i.e., line to ground fault. Hence, this mode can be used in classifying fault types whether they are ground faults or not. The second mode, also known as the aerial mode, however, is present for any kind of fault. Accordingly, the fault location problem is formulated based essentially on the aerial mode, making occasional use of the ground mode signal for purposes of distinguishing between certain special situations.

## 2.2 Wavelet Transform and Peak Detection

A key issue in fault detection and location is to obtain useful signal components for frequency and time from the fault transient on the line. For fault location using traveling waves, high frequency content is more important. Hence, it is necessary to separate the high and low-frequency components from the transient disturbances. Such separation can be achieved by the processes of approximations and details in wavelet transform analysis [5]. The approximations are the high-scale, low-frequency components of the signal, while the details are the low-scale, high-frequency components. Of course, wavelet transform has a time window, and time information as well frequency information can be determined. As a result, wavelet analysis can be used effectively to separate discontinuities from traveling transients on a faulty line.

For a given function  $f(t)$ , its continuous wavelet transform is defined as follows:

$$WT(f, a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \varphi^* \left( \frac{t-b}{a} \right) dt \quad (5)$$

where  $a$  and  $b$  are the scaling (dilation) and translation (time shift) constants, respectively, and  $\varphi$  is the wavelet function (called mother wavelet) which may not be real as assumed in the above equation for simplicity. Wavelet transform of sampled waveform can be obtained by implementing the discrete wavelet transform (DWT) which is given by

$$DWT(f, m, n) = \frac{1}{\sqrt{a_0^m}} \sum_k f(k) \varphi^* \left( \frac{n - ka_0^m}{a_0^m} \right) \quad (6)$$

where parameters  $a$  and  $b$  in Eq. (5) are replaced by  $a_0^m$  and  $ka_0^m$ ,  $k$  and  $m$  being integer variables.

Actual implementation of DWT involves successive pairs of high- and low-pass filters at each scaling stage of the wavelet transform. How to separate frequency components or find discontinuity from transients is not unique, even though using wavelet analysis, because various wavelet functions exist. In principle, any one of various wavelet functions can be used, Daubechies wavelet, db4, has been chosen as the mother wavelet.

Using wavelet transform, we can decompose monitoring signals into high-frequency components with a finite time window. Generally, amplitudes and times of detailed signals vary with resolution, and the signals are usually scattered. Therefore, it is very important to determine the correct peak times that faulty travel waves reach the monitoring position. Most peaks are located within a narrow time interval and their peak values are not regular. In order to determine fault location correctly, it is important to classify the order of peaks. Generally, the first peak can be classified easily but most peaks

may be less distinguished because of low amplitudes and scattering. Hence, sometimes, a mistake is made in obtaining the correct fault location. Finally, correct time results can be obtained depending on the peak detection algorithm. In general, peaks are defined as local maxima, i.e., it is a maximum value between two consecutive local minima [6]. For locating and measuring the peaks in transient time signals, first, it must detect peaks by looking for downward zero-crossing in the smoothed first derivative of signals. And then, position, height and width of each peak are determined using least-squares curve-fitting. To find suitable peaks in the traveling wave, there are several factors such as slope threshold and amplitude threshold to be chosen a priori.

### 3. Fault Location Algorithm

When a fault occurs on a transmission line, the speeds of aerial mode and ground mode of traveling wave appear different values [2], [7]. To illustrate the propagation phenomenon of traveling wave, the Bewley's lattice diagram can be used. Consider a fault for the power system shown in Fig. 1 at close-in and remote-end distances respectively from bus A. Fig. 2 and 3 show the reflection and refraction diagram for traveling wave when a fault occurs at the near and remote half of the line as referring to the half distance of the line, i.e., the middle of the line.

#### (a) $L_x \leq L/2$ Case

When a fault occurs in the first half of the middle of the line, the lattice diagram can be given as Fig. 2. There are three types of modes, i.e., ground, alpha and beta modes, but ground and alpha mode are often used in analyzing traveling speeds or wave

performances for fault detection and location. Theoretically, the speed of alpha mode equals that of beta mode. Therefore, only the ground and alpha mode will be analyzed, hereafter.

The ground mode speed is less than that of alpha mode, and, the first peak of the ground mode reaches lately to the bus A. Under the assumption that fault distance is determined by using time intervals between the first two peaks of each mode, the differences of two modes defined as

$$t_{id} = t_{i2} - t_{i1}, \quad \forall \quad i = g, \alpha \quad (7)$$

are increased in proportion to fault distance, for  $L_x \leq L/2$ , where  $i=g$  and  $a$  mean the ground and alpha mode case for the simplicity of notation. If we can determine the first two peaks for each mode and its difference from the coefficients decomposed by the wave transform, the fault location is calculated by the following equations:

$$L_{xi} = v_i \times \frac{t_{id}}{2}, \quad \forall \quad i = g, \alpha \quad (8)$$

where  $v_i$  ( $i=g, a$ ) is the propagation speed of ground and alpha mode, respectively, and these values are assumed to be known a priori.

To calculate the fault location using Eq. (7) and (8), at least, two times of the four peak points ( $t_{a1}$ ,  $t_{a2}$ ,  $t_{g1}$ ,  $t_{g2}$ ) can be properly determined. Of course, in most fault cases, it may be possible to get two or more peak points for ground and alpha mode in a finite analysis time. If the first two peaks for each mode can be found correctly, for the given wave speed, quantitative error due to finite sampling frequency in data acquisition system always exists, and then, error detection error cannot be inevitable. In order to enhance reliability of estimation result, it is important to detect the correct peak points

appearing in high-frequency transients when surges traveling on the line reach the monitoring bus. As a consequence, to obtain a reliable fault location, first, a suitable signal processing tool is selected to show surge phenomenon evidence, and second, designing a peak detector with good performance is necessary.

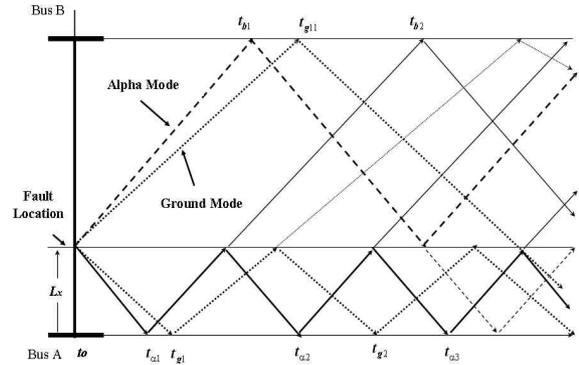


Fig. 2. Lattice diagram for  $L_x \leq L/2$

If the time difference between the first two peaks for ground and alpha mode is given as

$$t_{gad1} = t_{g1} - t_{a1} \quad (9)$$

then it can be used in selecting the fault algorithm, which is applied to two regions of fault location. The time difference will be denoted as  $t_{dm}$  in the middle of the line,  $L_x=L/2$ . Sometimes, it may be directly used in calculating fault distance [2], but it is used to choose the fault algorithm. For example, if  $t_{gad1} \leq t_{dm}$ , then  $L_x \leq L/2$ , and Eq. (9) is chosen to calculate fault distance.

Peaks can be produced at correct times when the surges occurring in a fault point of the line reach the monitoring location. However, such peak points cannot always be determined with satisfactory values because the peak detector has various factors to consider such as bandwidth, slope, detecting width, filter, and so on. Therefore, in the procedure

of applying Eq. (2) and Eq. (8), whether peak points are determined properly or not should be examined, and after calculating fault distance using Eq. (7), its validation should be checked.

(b)  $L_x > L/2$  Case

For a fault distance located in the middle of the line,  $L/2$ , the second peak point,  $t_{i2}$ , generated at bus A by the forward traveling wave appears at the same location as the peak point generated at bus B by the reverse traveling wave. As mentioned above, the difference between the first two peaks of the traveling wave linearly increases as the fault distance increases from zero to the middle of the line while it adversely decreases as the fault distance over the middle of the line increases. As a result, a fault in the middle of the line shows the maximum difference between the first two peaks for each mode, i.e.,  $t_{gdm}$  and  $t_{adm}$ . Finally, one of the two different algorithms should be applied suitably.

If a fault occurs in the second half of the line, the propagation phenomenon of surges monitored at bus A are more complex due to reflection and refraction signals at an early period of time, as shown in Fig. 3. Unlike  $L_x \leq L/2$ , in the case of  $L_x > L/2$ , the second peak of the monitoring signal for each mode at bus A is the peak generated by the reflection wave of the reverse direction traveling wave. As the fault location increases to the other end of the line, this second peak point  $t_{i2}$  decreases while the first peak point  $t_{i1}$ , increases. Finally, if  $L_x = L$ , then  $2t_{gdm}$  and  $2t_{adm}$  for ground and alpha mode.

Even in this case, the fault location can be calculated using the four peak points ( $t_{a1}$ ,  $t_{a2}$ ,  $t_{g1}$ ,  $t_{g2}$ ) similar to the case  $L_x \leq L/2$ . And the maximum difference of the first two peaks,  $t_{im}$  ( $i=g,a$ ), for each mode when a fault occurs in the middle of the line is known a priori by numerical analysis. After

calculating  $t_{id}$  given in Eq. (7), it will satisfy the equality,  $t_{id} > t_{im}$ , i.e.,  $L_x > L/2$ . Hence, the fault location can be calculated using the following equation.

$$L_{xi} = L - v_i \times \frac{t_{id}}{2}, \quad \forall i = g, \alpha \tag{10}$$

As described in the lattice diagram, the difference between the first two peaks for alpha mode is a linear function of fault distance to the middle, and shows a reverse proportion to fault distance after the middle of the line. It is the same for the ground mode. As a result, there are two different routines to design after verifying the fault distance. In this paper, evaluation criterion to select the calculating equation of the fault location uses the difference between the first two peaks for ground mode and alpha mode at the half length of the line, i.e.,  $L_x = L/2$ . This is pre-determined using known information and assumption of the transmission line.

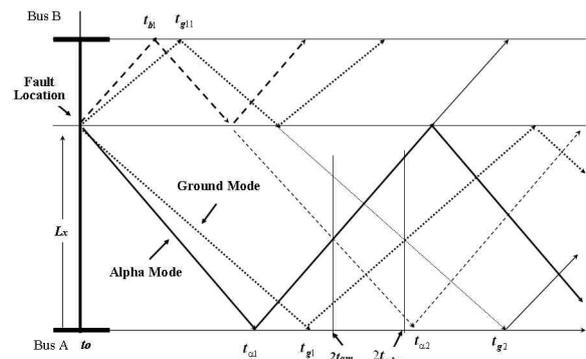


Fig. 3. Lattice diagram for  $L_x > L/2$

(c) Validation

Due to quantization error generated by a finite sampling frequency, calculation errors may exist for different speeds. Note that the minimum error is  $\pm 1$  count by the sampling system, and then, fault estimation error becomes  $1/2$  of  $\pm 1$  count error

according to Eq. (8) and (9). Decomposition of high-frequency components by wavelet transform, and design of peak detector with thresholds may cause uncertainties in determining any unique solution. If the difference between the two results is too large, or any other condition is not satisfied, then, a suitable result has to be selected. However, it may not be easy to decide which result has to be chosen. Furthermore, we can use several indices to validate fault locations. Basically, the following equation can be examined for  $L_x \leq L/2$

$$t_{g\alpha 2} = 3 \times t_{g\alpha 1} \quad (11)$$

When  $L_x > L/2$ , from the lattice diagram, Fig. 3, the following relation

$$\delta_i = |2t_{im} - t_{id} / 2|, \quad \forall i = g, \alpha \quad (12)$$

is determined. Then the value for the mode satisfying  $\min(\delta_g, k\delta_\alpha)$  can be chosen as the final result of the fault location, where  $k = t_{gm} / t_{\alpha m}$ .

## 4. Simulation and Discussion

### 4.1 Fault Transmission Line

To analyze fault location with the traveling speed of wave, SimPowerSystems toolbox in Matlab is used. The 154[kV] transmission line with ACSR 410 [mm<sup>2</sup>] bundle conductors installed with a horizontal tower configuration is represented as a distributed parameter model. Phase voltages as fault signals are monitored at bus A, with a sampling time of  $T_s = 1 \mu s$  for all simulation cases. The transmission line is well transposed, and its length is 100[km]. A variety of faults for the purpose of numerical analysis are used as follows:

- (1) 11 types of faults, i.e., every three cases for single-phase line to ground fault, double-phase to ground fault, and double-line fault, respectively, including a three-phase to ground fault and a three-line fault.
- (2) 11 different fault locations, i.e., every ten km including 1 and 99[km].

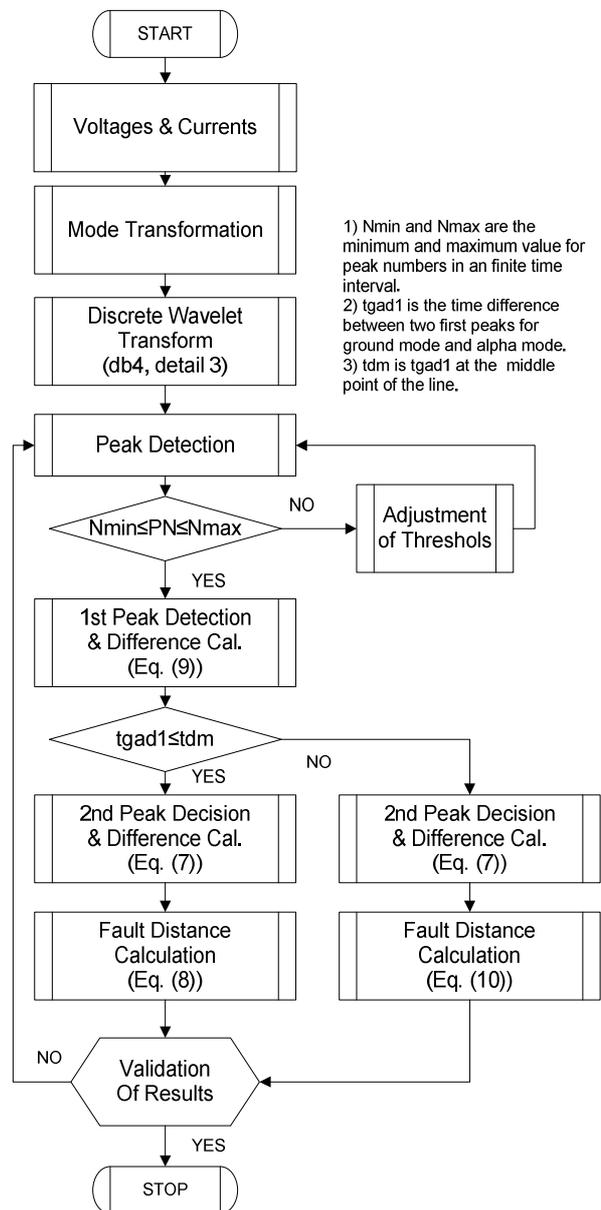


Fig. 4. Proposed algorithm of fault location

Phase voltages are transformed to mode components using Clarke’s transformation matrix, Eq. (4). Ground mode and alpha mode of two aerial modes are used. In order to decompose high-frequency transients from traveling waves, DWT with a mother wavelet, Daubechies *db4* is employed and then, coefficients of detail *d3* obtained by wavelet transform are squared in order to minimize the noise effect and discriminate high-frequency components. Fig. 4 demonstrates the calculation routines given in Section 3.

## 4.2 Numerical Examples

### 4.2.1 Propagation Speed and Basic Description

The propagation speeds for ground mode and aerial mode based on the line parameters are calculated by  $v_g=2.373 \times 10^5$  and  $v_a=2.938 \times 10^5$  [km/s], respectively. Since the sampling time is chosen by 1 us, the error of  $\pm 1$  count of the data processing system becomes about  $\pm 237$ [m] for ground mode and  $\pm 294$ [m] for aerial mode, respectively. However, all fault locations to be obtained by Eq. (8) and (10) would contain at least  $\pm 0.12$  and  $\pm 0.15$ [%] for each mode, respectively, for the line length, because  $\pm 1$  count error for sampling signal shows a half when calculating fault distance.

As described in Section 3, there are two different characteristics depending on where the fault appears, in particular, referring to the middle of the line. When a fault occurs in the first half of the line, transient characteristics showing peak points are somewhat simple. In general, the first peak is more significant than other peaks. Therefore, using the first two peaks of the ground mode and alpha mode, an index as to whether the fault location is in a closed-in or remote-end of the line is determined. By choosing the sampling time of 1 us, the scale of

the time axis is represented by a sample number instead of us, for the simplicity of analysis. In addition, the percentages for the maximum amplitude of peaks to represent peak performances clearly, are used. For example, Fig. 5 shows details for a three-phase to ground fault located at a distance, 50[km]. From this figure, the fault distance is calculated by  $v_g \times (512 - 170)$  us, and it is about 50.23[km].

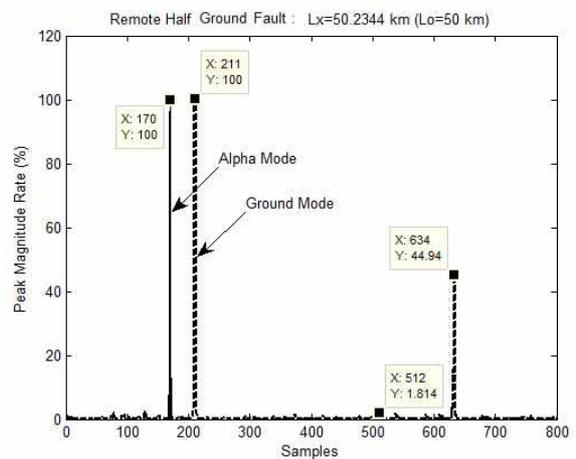


Fig. 5. Peak Performances for a three-phase to ground fault at 50[km] from bus A

### 4.2.2 Fault Location

To detect fault distance based on peak points monitoring traveling waves, it is necessary to find any strategy to separate and detect peaks correctly from transient signals. In the case of a single-ended monitoring system, peak performances appearing at a monitoring point show very complex characteristics due to signals from the fault point to travel directly there, and waves reflected from the remote end of the line. The time difference between the first two peaks for ground mode and alpha mode is a linear function of fault distance before and after the middle point of the line.

For example, Fig. 6 shows fault location estimates and their errors for 11 fault distances, for phase

A-to-ground fault. As a result of simulation, the maximum error of estimation is about 0.21[%] and the fault location estimate has perfect proportion to the actual distance. For ten types of faults at the distance of 30 and 80[km], the maximum errors are given as 0.15, and 0.23[%], respectively, which belong within about twice of the quantization error,  $\pm 0.12$ [%](simulation results not given here).

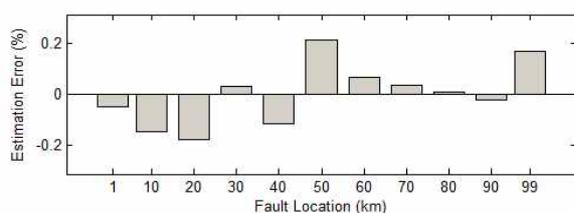


Fig. 6. Fault location estimates and their errors

#### 4.2.3 Inception Angle and Fault Resistance

Inception time of fault and fault resistance are also main factors affecting the detection results. If a fault occurs at the time of angular velocity  $\omega = \pm n\pi$ , ( $n=0, 1, 2, \dots$ ) or  $\omega = \pm(2n-1)\pi/2$ , ( $n=0, 1, 2, \dots$ ) for the signal of a faulty line, surge changes are usually negligible. However, when a fault invades at the time of signal, transients become significant. In most fault locations, insignificant changes of frequency components and amplitudes of traveling waves lead to suffer to obtain satisfied results. In order to examine the performance of the suggested algorithm, it is assumed that a single phase to ground fault occurs at a distance 30[km], for nine different inception angles,  $\phi = n \times 45^\circ$ , ( $n=0, 1, \dots, 8$ ). Fig. 7 shows the estimation performances, and fault locations can be obtained somewhat to correct values, with the maximum error of only 0.26[%].

On the other hand, fault resistance would be sensitive whenever any impedance method is used [3]. However, the traveling wave method is less

sensitive than the impedance method, depending on designing peak detector. To examine the fault resistance influence, different fault types are considered at the fault distance of 60[km], with suitable 10. The developed method was verified as having good accuracy for various fault resistances.

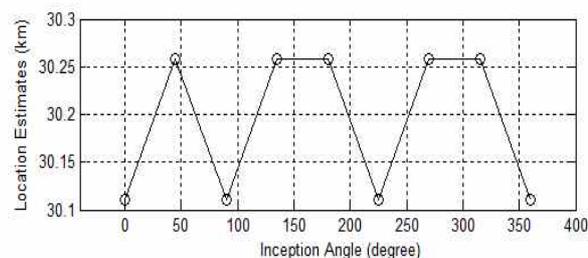


Fig. 7. Fault location estimates for varying inception angles and fault resistance

## 5. Conclusions

An improved method for fault location based on single-ended measurement is described in this paper. Traveling wave theory together with the wavelet transform is used. To detect fault distance on an overhead transmission line, transient signals generated at a fault point are monitored at the single-ended of the line. In estimating fault location, a simple fundamental method using the time difference among peaks of transient signals is considered, but a new method is needed in order to increase measurement sensitivity and enhance its accuracy.

For the purpose of designing fault location system, one method is how to represent the correct position and significant amplitude of the peak at the monitoring bus, as well as to detect the correct time of the first, or second peak. The other consideration is how to establish a suitable relationship among the peaks for the ground mode and aerial mode, in order to increase fault location accuracy. The algorithm

was developed with reference to a lattice diagram for ground mode and alpha mode of the traveling wave. Based on this diagram, we can find a new way to increase recognition rate or measurement accuracy of fault location. Adopting such a relationship into a fault location system, various cases for fault types, fault locations and fault inception angles, under study of a transmission line configuration, are analyzed.

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### Biography



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