Accurate location of faults on power transmission systems can save time and resources for the electric utility industry. Line searched for faults are costly and can be inconclusive. Accurate information needs to be acquired promptly in a form most useful to the power system operator. In order to attain this accuracy, a complete system of fault location technology hardware, communications, and software can be designed. The manuscript describes the phenomenon of traveling waves generated due to different faults in transmission lines and how these waves can be used to obtain precise fault location in very little time.

Keywords: Transmission lines, Fault location, Traveling waves, Impedance fault locators.

1. INTRODUCTION

The power transmission line is the most frequently faulted element of a power transmission system [1, 2, 3]. There are numerous possible causes of such faults. The causes include short circuits, faulty equipment, mis-operation, overload, aging of system components, lightning, and human errors. Faults result in short to long term power outages for customers and may lead to considerable losses. Thus, determination of fault location in high voltage power transmission lines is a major issue for electric utility industry. Fault location can be performed for the proper operation of power system protection devices or for the effective inspection of power transmission line. In the former case, fast localization is crucial, while the accuracy may be limited only to correctly identifying the protection zone. In the latter case, it is important to precisely determine fault location.

Accurate fault location can aid in the fast restoration of power, particularly on transmission lines with distributed loads. Power system operators can identify and isolate faulted sections on tap-loaded lines and remove them by opening circuit breakers or switches remotely along the line, restoring power to the tap loads serviced by the unfaulted transmission sections.

A detailed review of different fault location techniques is presented in [4]. Among the most important types of fault locators are: impedance and traveling wave locators. Impedance locators can be a part of power system protection device. The traveling wave locator works as an independent device.

2. COMPARISON OF IMPEDANCE AND TRAVELING WAVE FAULT LOCATION METHODS

Impedance-based fault locators are a popular means of transmission line fault locating. They use algorithms that correct for fault resistance and load current inaccuracies. Line length accuracies of ±5% are typical for single-ended locators and 1-2% for two-ended locator systems.
Operation of impedance locators is based on the measurement of currents and voltages during fault. Due to the use of these two electrical quantities in fault locating algorithm, there are errors caused by:

- transient component of current
- deformation of the current in the core as a result of saturation of current transformers
- fault resistance in fault location
- earth capacitance
- magnetic coupling between circuits in lines
- inaccuracies in the impedance of transmission line, especially, uncertainty associated with the determination of the zero sequence line impedance

Speaking of traveling wave fault location, the faults on a power transmission system cause transients that propagate along the transmission line as waves. Each wave is a composite of frequencies, ranging from a few kilohertz to several megahertz, having a fast rising front and a slower decaying tail. Composite waves have a propagation velocity and characteristic impedance and travel near the speed of light away from the fault location toward line ends. They continue to travel throughout the power system until they diminish due to impedance and reflection waves and a new power system equilibrium is reached.

The location of faults is accomplished by precisely time-tagging wave fronts as they cross a known point, typically in substations, at line ends. With waves time tagged to submicrosecond resolution of 30m, fault location accuracy of 300m can be obtained. Fault location can then be obtained by multiplying the wave velocity by the time difference in line ends. This collection and calculation of time data is usually done at a master station. Master station information polling time should be fast enough for system operator needs.

Traveling wave fault locators are becoming popular where higher accuracy is important. Long lines, difficult accessibility lines, high voltage direct current (HVDC), and series-compensated lines are popular applications. The travelling wave technique has been applied to the protection of power transmission systems as described in [5-11]. Accuracies of less than 300 meters have been achieved on 500 kV transmission lines with this technique.

For a traveling wave locator, the key factors influencing the error of determining the distance to fault are as follows:

- small fault angle
- faults close to the place of locator installation
- synchronization errors of device
- incorrectly determined wave propagation velocity in high voltage line
- errors associated with detecting traveling wave
The term small fault angle refers to the situation of fault occurrence when the instantaneous value of voltage is close to zero. This causes problems in detecting the fault due to the small amplitude of the generated electromagnetic wave. Only, when there is a rapid change of voltage, it is possible to generate voltage and current wave with appropriate amplitude. This problem can be eliminated by the simultaneous determination of the fault location by both traveling wave and impedance fault locators.

The error associated with faults occurring close to the place of installation of traveling wave fault locator, which causes multiple wave reflections between the place of installation and the place of fault locator, may be eliminated due to high frequency sampling. The synchronization error occurs for fault location realized on both ends of transmission line (type D method). This error is usually equal to ±1µs, which causes error in distance determination equal to ±150 m for one locator.

The wave propagation velocity is one of the quantities, which is used to calculate the distance to fault location. It depends both on the transmission line parameters and on the path of wave propagation. The error of detecting traveling wave is associated with phenomenon during which amplitude of wave increases and propagating wave elongates. If fault occurs closer to the substation A than B, due to the increased elongation of the wave front reaching the station B, the detection of waves in the station will occur later and it will introduce additional error.

Traveling wave fault locators exhibit accuracy of determining distance to fault within a range of 150-500 m independent of increased to line length. This accuracy also applies to long lines that are series compensated. High accuracy of locating faults, increased power system reliability, and cost savings have resulted from the use of traveling wave fault locators. They are widely used in countries such as USA, China, South Africa, Scotland, and Canada.

3. TRAVELING WAVE PHENOMENON

Traveling wave phenomenon in high voltage lines constitutes one of the shortest system transients. It occurs from microseconds to milliseconds. Traveling waves are associated with the propagation of electromagnetic waves which result from the short-circuits in transmission lines and the lightning or switching operations in power system. A sudden and significant change in voltage in at least one place within the high voltage line (Figure 1) leads to the initiation of an electromagnetic wave which propagates from that point in opposite directions.

![Figure 1: Propagation of electromagnetic wave as a result of fault](image)

Electromagnetic wave can be divided into a voltage wave associated with phenomena occurring in the electric field and a current wave associated with the magnetic field. An important feature of such a wave is moving the specific values of voltage and current along the lines with finite speed.
The use of wave phenomena in fault location requires an examination of a number of theoretical issues such as:

- wave velocity in transmission line
- model of transmission line with distributed parameters
- attenuation and distortion of waves
- transition and reflection of waves
- modal transform
- wavelets transform

The accuracy of traveling wave fault location depends on a proper determination of wave velocity in the transmission line. The speed of wave propagation depends on the transmission line parameters, which vary with the changes in ambient temperature, icing, and dirt on phase conductors. The wave velocity also depends on the path of wave propagation. So, it is determined separately for earth and non-earth faults. Wave velocity in aerial-mode propagation is approximately \( v = 295000 \) km/s [12], while in ground-mode propagation its value is estimated at \( v = 188000 \) km/s [13]. During installation of traveling wave fault locator, the propagation speed can be determined by generating a wave in the transmission line by switching capacitor banks to the transmission line or by closing a circuit breaker.

The model of transmission line with distributed parameters is characterized mainly by the fact that the signal appearing at the input needs a specific time to appear at its output. These circuits are described by partial differential equations. Voltages and currents in this circuit are a function of two variables - the time “\( t \)” and the position “\( x \)”.

Transmission lines that operate at a frequency of 50 Hz and are shorter than 6000 km are modeled as a lumped circuit. However, if the frequency increases, for example, to 100 kHz, even a 3 km long line has to be regarded as a circuit with distributed parameters.

Attenuation and distortion of waves due to their propagation along the transmission line result in a decreasing of amplitude and elongation of the wave. This is due to a loss of energy in the resistances of power line conductors and earth, charging capacities of insulators, and corona effect [13]. The transition and reflection of waves also result in their attenuation and distortion at the points of change of surge impedance. Surge impedance determines the ratio between the amplitude of voltage and current wave propagating along the transmission line. If the incoming wave encounters point of change in impedance, part of the wave energy is reflected from this point, and part through it.

Modal transformation is used to perform analysis of three-phase lines as three separate single-phase lines without magnetic coupling between them. Theoretically, there are infinitely many modal transformations, of which the most widespread is the symmetrical components transformation. However, for the analysis of traveling wave phenomena, this transformation does not apply. This is due to the nature of the phenomena described by instantaneous values of voltages and currents, which cannot be converted into a zero, positive and negative sequence.
Wavelet transform is used for the analysis of nonstationary signals. The statistical characteristics (mean, rms, correlation functions) of these signals are functions of time (depends on the choice of the initial moment). One of the most important features of wavelet transform is the ability to determine the time at which there is a high-frequency signal and the ability to examine the components of low frequency signal at the same time.

4. MEASURING METHODS

Traveling wave fault locators can be divided into five different types: A, B, C, D, and E, according to the measuring method used. These five types are discussed in [14, 15, 16]. The operation of each type of locator is based on the analysis of the incoming electromagnetic wave resulting from a fault. Description of only A, D, and E types of locators will be presented here because the other methods, that is, B and C, are obsolete and the modern traveling wave fault locators do not use them.

4.1 Type A locators

Type A locators perform measurements on one end of the line. The distance to the fault location is calculated by measuring the time between the moment when the wave generated by fault will reach the fault locator and the moment when the wave reflected from the fault location reaches the fault locator. The electromagnetic wave is reflected completely from the fault location when the arc in fault location has a lower resistance than the characteristic impedance of line. The transmission line and the wave propagation are shown in Figure 2.

Figure 2: Type A fault locator method and lattice diagram

The distance to fault location from substation A can be calculated using the following equation:
\[ D = \frac{t_3 - t_1}{2} \cdot v \]  

(1)

where:

\( D \) – distance to the fault location [m]

\( t_1 \) – time when first wave generated at fault location arrives at substation A [s]

\( t_3 \) – time when first wave reflected from fault location arrives at substation A [s]

\( v \) – wave velocity [m/s]

The measurement error of type A locator depends on the duration of fault arc, fault resistance, and the problems with identification of appropriate wave. These errors are eliminated with the use of type D fault locator.

4.2 Type D locators

Type D locators perform measurements on both ends of the line. The waves generated at the fault location run in opposite directions, to substations A and B, and they reach there in few microseconds. For a correct determination of distance, D-type fault locator requires the use of two synchronized devices installed at both ends of the line. Synchronization between the devices is realized by using a GPS system. The fault locator determines the time difference, when waves reach substations A and B, which is then used to calculate distance to fault. Transmission line and the wave propagation are shown in Figure 3.

\[ D = \frac{L + (t_A - t_B)}{2} \cdot v \]  

(2)

where:

\( L \) – length of the transmission line [m]

\( t_A \) – time when first wave generated at fault location arrives at substation A [s]

\( t_B \) – time when first wave reflected from fault location arrives at substation B [s]
\( t_A \) – time when the first wave generated at fault location arrives at substation A [s]

\( t_B \) – time when the first wave generated at fault location arrives at substation B [s]

L – length of line [m]

\( v \) – wave velocity [m/s]

### 4.3 Type E locators

Type E locators perform measurements on one end of the transmission line. They use wave which is generated by closing circuit breaker on transmission line. In its operation, type E method is similar to impulse-reflectometry method used to locate faults in cables. The circuit breaker which closes in transmission line can be treated as three separate impulse generators.

The time difference between the pulse generated by closing a circuit breaker and a reflected impulse from the fault is used to determine the distance to the fault. The principle of operation of type E fault locator is presented on Figure 4.

![Figure 4: Type E fault locator method and lattice diagram](image)

The distance to fault location from substation A can be calculated using the following equation:

\[
D = \frac{t_2 - t_1}{2} \cdot v
\]

(3)

where:

D – distance to fault location [m]

\( t_1 \) – the time when wave is generated by closing a circuit breaker [s]

\( t_2 \) – the time when reflected wave reaches a substation [s]

\( v \) – wave velocity [m/s]
Type E locators can be used for detection and localization of broken conductors. Moreover, it is possible to check if the electric length of healthy transmission line is equal to the length of line measured by the use of a different method.

5. DESCRIPTION OF BASIC ELEMENTS OF MEASURING SCHEMES OF TRAVELING WAVE FAULT LOCATORS

Due to the nature of traveling wave phenomena, it is important to analyze elements of measurement schemes used for the proper operation of travelling wave fault locators, that is,

- current and voltage transformers
- digital signal processing schemes
- satellite navigation systems

At the beginning of development of traveling wave fault locators, voltage transformers were used to detect travelling waves, but due to the unsatisfactory frequency response of voltage transformers, presently current transformers are primarily used. Fault location is realized through a use of the protection current transformers, which properly transfer frequency up to 100 kHz [17, 18].

The traveling wave fault locators need appropriate schemes, to be able to receive and analyze big amount of data and to properly identify waveforms arriving to the device [19]. The fault locator also requires application of a sampling frequency not less than 1 MHz, to the data acquisition system. The higher the sampling frequency of the input signal, the more accurate is the result. But the higher sampling frequency increases the load of the processor and requires more memory capacity to store the data.

Synchronization of fault locators installed on both ends of transmission line is realized through the use of a GPS. The time synchronization error is estimated to be 1 µs, which is equal to ±150 m error of determining fault location for a single fault locator. European satellite navigation system Galileo provides an opportunity to reduce this error. The accuracy of GPS receivers is estimated to be a few meters, while Galileo error will reach an accuracy lower than 1 m in 2012 [20].

6. CONCLUSION

Unlike the impedance measurement methods which can locate short-circuit faults in normal AC power lines only, traveling wave technique can be used to measure distance to fault in all kinds of power lines, including

- AC transmission lines
- HVDC transmission lines
- Seriously compensated transmission line
- Lines with T branches
- The line containing cable sections and overhead line
• Measuring fault distance of a single phase to ground fault in non-effectively earthed distribution system

The commonly used traveling wave fault location methods include A, D, and E. Type E Method makes use of transients generated when a circuit breaker is closed to a dead line.

Type D method is simpler and considered to have a very good accuracy and reliability in field operations. Type E method is very efficient in locating conductor broken fault. Type A method is more cost effective, but its reliability is compromised by the difficulty to discriminate fault reflections from the pulses introduced by the reflections from other line terminals and nonlinearity of fault arc.

LIST OF SYMBOLS
- \( D \): distance to the fault location [m]
- \( v \): wave velocity [m/s]
- \( L \): length of power transmission line [m]

REFERENCES


