

Transmission Line Protection using Traveling Wave Polarity Comparison

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ABSTRACT: Currently, the fault clearing time takes a few power cycles, in which part of this delay is due to the slow fault detection accomplished through fundamental frequency-based protection systems. So new protection schemes has been developed based on traveling wave. This paper demonstrates that the traveling wave-based protection provides a high speed and very accurate fault detection. The given method compares the polarities of current and voltage traveling waves measured immediately after the fault inception to determine the fault direction. Major advantage is operation independent of fault distance, fault inception angle, fault path resistance, and the method used for neutral grounding.

KEYWORDS: Traveling wave, Fault clearing time, High-speed protection, Refraction and Reflection, Electromagnetic transients, Fault inception time.

I. INTRODUCTION

The power system grown rapidly over the last few decades, so large number of power transmission line are required with the fast and accurate transmission line fault location estimation, which is essential to reduce the restoration time of power system. Fundamental frequency-based protection system required the large operation time, which has motivated the development of reliable and high speed protection schemes [1].

When a fault takes place upon an overhead transmission line, the abrupt change in voltage at the fault point generates electromagnetic impulses, which propagate along the line as traveling waves in both directions away from the fault point. When these voltage and current waves reach the nearest line terminal, the first wave-front arrival time registered as the fault inception time at related bus. Refractions and reflections will occur at the line terminals, which are considered discontinuities for the traveling waves. Therefore, reflected waves will propagate back along the line towards the fault position, where further reflected and transmitted waves will initiated. After some time, various waves can coexist in a specific line point due to the principle of the wave superposition. The aforementioned phenomena yield electromagnetic transients at both line terminals, which is used for protection purposes [2].

Depending upon the fault distance, low and high frequency transients are generated in voltage and current at each line terminal, providing extensive information about the fault type, inception time, location, and direction [3],[4]. In the literature on the subject of fault location in transmission lines, several algorithms have reported. Among them, impedance-based approaches are the most used by utilities due to their simplicity and low computational burden [5],[6]. However, these fault-location algorithms are usually quite sensitive to power system load flow, large fault resistance, and series compensation [7]. For that reason, the traveling-wave-based FLs have been increasingly used as an alternative to overcome such drawbacks, since their accuracy depends mainly on the data-acquisition system sampling rates and time synchronization [8],[9].

For many years, one-terminal traveling-wave-based methods were recognized by utilities as a good way to overcome the shortfalls of impedance-based approaches [2]. In fact, one-terminal techniques are able to provide a quick fault location and do not require data synchronization. However, these methods commonly have problems of locating close-in faults and of distinguishing between traveling waves reflected from the fault and from power system terminals, reducing the FLs reliability. Among the traveling-wave-based fault-location algorithms, for locating faults in a given two-terminal line, those that use data from both line ends are reported as the ones which provide the best cost benefit, as they are simpler than multi-terminal fault-location methods (which require monitoring devices at more than two

terminals) and are less susceptible to errors than one-terminal methods [2]. However, conventional two-terminal techniques require, as a rule, the data from both line ends to be synchronized, which is often reported as a drawback that can jeopardize the accuracy of two- and multi-terminal traveling wave-based FLs [10].

In this paper, a two-terminal traveling wave based algorithm is discussed to locate faults in real time using unsynchronized data. It is non-iterative and only requires that the substations at both line ends are linked by a dedicated communication system with a small latency variability, whose data-transmission delay is known or can be estimated. The algorithm was evaluated by means of a wide variety of faults in a 230- kV, 200 km long transmission line, assuming the existence of communication links connecting FLs in both monitored line ends. The obtained results indicate that the proposed algorithm is reliable and quite useful for power systems in which there is no common time reference source available, since it is able to indicate, in most cases, the correct fault location, even using communication systems with large data-transmission latency variability.

II. PROBLEM FORMULATION

A) Fault Detection-

Consider a single line system with distributed parameter. A differential element dx is considered at distance x km away from sending end shown below

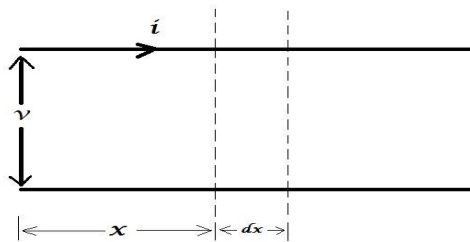


Fig.1: Transmission line distributed parameter [8]

We know that,

$$\frac{\partial v}{\partial x} = Zi$$

And,

$$\frac{\partial i}{\partial x} = Yv$$

Differentiate above equation

$$\frac{\partial^2 v}{\partial x^2} = Z \frac{\partial i}{\partial x}$$

$$\frac{\partial^2 v}{\partial x^2} - ZY * v = 0$$

Solving above differential equation

$$v(x) = K_1 e^{-\gamma x} + K_2 e^{+\gamma x}$$

$$\text{Where } \gamma = \sqrt{YZ}$$

$$i(x) = \frac{1}{\sqrt{Z/Y}} (K_1 e^{-\gamma x} - K_2 e^{+\gamma x})$$

Where K_1 and K_2 are constant

These equations are valid only at some fixed time, i.e. it is assumed that $v(x)$ and $i(x)$ are function of distance x along line. Since voltage and current are function of time and distance equation need to modified

$$v(x, t) = f_1(t)e^{-\gamma x} + f_2(t)e^{+\gamma x}$$

And

$$i(x, t) = \frac{1}{\sqrt{Z/Y}} (f_1(t)e^{-\gamma x} - f_2(t)e^{+\gamma x})$$

Assume lossless line

$$R = G = 0$$

$$\sqrt{ZY} = \gamma$$

$$\sqrt{Z/Y} = Z_0$$

$$v(x, t) = f_1(t)e^{-\gamma x} + f_2(t)e^{+\gamma x}$$

$$i(x, t) = (f_1(t)e^{-\gamma x} - f_2(t)e^{+\gamma x})/Z_0$$

Using $\{e^{\pm ap} f(t) = f(t \pm a)\}$

$$v(x, t) = f_1\left(t - \frac{x}{c}\right) + f_2\left(t + \frac{x}{c}\right)$$

$$i(x, t) = \left[f_1\left(t - \frac{x}{c}\right) - f_2\left(t + \frac{x}{c}\right) \right] / Z_0$$

Combining above equation

$$i(x, t) + \frac{1}{Z_0} v(x, t) = 2f_1\left(t - \frac{x}{c}\right) / Z_0$$

At Sending end $x = 0$ and Receiving end $x = l$

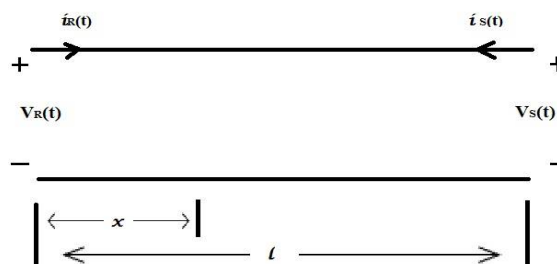


Fig.2: Single-phase line used to explain BERGERONS EQUATION [8]

$$i(0, t) + \frac{1}{Z_0} v(0, t) = 2f_1(t) / Z_0$$

$$i(l, t) + \frac{1}{Z_0} v(l, t) = 2f_1\left(t - \frac{l}{c}\right) / Z_0$$

We know that

$$\begin{aligned} i(0, t) &= i_R(t) \\ v(0, t) &= v_R(t) \\ i(l, t) &= -i_S(t) \\ v(l, t) &= v_S(t) \end{aligned}$$

We obtained BERGERONS EQUATION

$$i_R(t - \tau) + \frac{1}{Z_0} v_R(t - \tau) = -i_S(t) + \frac{1}{Z_0} v_S(t)$$

Where $\tau = \frac{l}{c} \rightarrow$ Surge transit time

Similarly

$$-i_R(t) + \frac{1}{Z_0} v_R(t) = i_S(t - \tau) + \frac{1}{Z_0} v_S(t - \tau)$$

Now this BERGERONS EQUATION can be used for detecting an internal fault. It can be best explained using single phase line model, such as shown in fig.3 whose voltage and current at two terminal of line are related by above equations.

Then this equation can be written in the form

$$\varepsilon_1(t) \triangleq i_R(t - \tau) + i_S(t) + \frac{1}{Z_0} [v_R(t - \tau) - v_S(t)]$$

$$\varepsilon_2(t) \triangleq i_S(t - \tau) + i_R(t) + \frac{1}{Z_0} [v_S(t - \tau) - v_R(t)]$$

For an external fault $\varepsilon_1(t) = 0$ and $\varepsilon_2(t) = 0$

For an internal fault $\varepsilon_1(t) \neq 0$ and $\varepsilon_2(t) \neq 0$

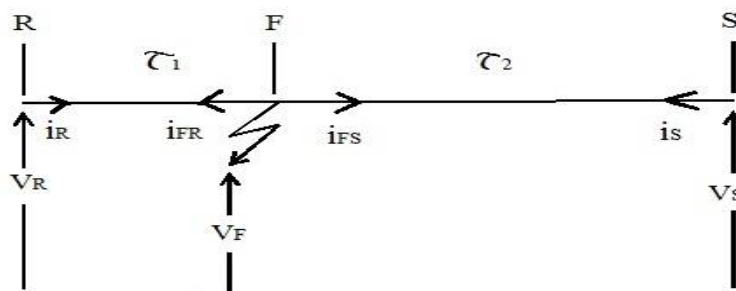


Fig.3: Single-phase line with internal fault [8]

It is possible to relate either of above function to fault current $i_f(t)$

$$i_{FS}(t - \tau_2) + \frac{1}{Z_0} v_F(t - \tau_2) = -i_S(t) + \frac{1}{Z_0} v_S(t)$$

$$-i_{FR}(t - \tau_2) + \frac{1}{Z_0} v_F(t - \tau_2) = i_R(t - \tau_1 - \tau_2) + \frac{1}{Z_0} v_R(t - \tau_1 - \tau_2)$$

Combining above equation and $\tau = \tau_1 + \tau_2$

$$i_R(t - \tau) + i_S(t) + \frac{1}{Z_0} [v_R(t - \tau) - v_S(t)] = -i_{FS}(t - \tau_2) + i_{FR}(t - \tau_2)$$

$$\varepsilon_1(t) = i_F(t - \tau_2)$$

$$\varepsilon_2(t) = i_F(t - \tau_1)$$

It will be evident that function $\varepsilon_1(t)$ and $\varepsilon_2(t)$ effectively describe the current in fault path. A non-zero value of $\varepsilon_1(t)$ and $\varepsilon_2(t)$ effectively signifies that fault exist between measuring point and a fact can be used to generate trip signal.

B) Fault Location-

Assume fault occurred at point f_1 shown in fig.

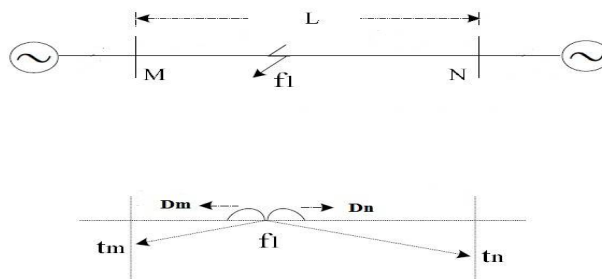


Fig.4: Single phase faulted system [8]

Location of internal fault is

$$D_m = \left[\frac{L + (t_m - t_n) * c}{2} \right]$$

$$D_n = \left[\frac{L + (t_n - t_m) * c}{2} \right]$$

Where $t_m \rightarrow$ Arrival instant time at M

$t_n \rightarrow$ Arrival instant time at N

$c \rightarrow$ Velocity of wave propagation

$L \rightarrow$ Length of protected line

III. PRINCIPLE OF TRAVELING WAVE PROTECTION

Considering a single phase system as shown in Fig.5, suppose $i(t)$ and $i(t)$ represent the initial current traveling wave observed at end M and end N respectively. According to the concept of fault generated traveling wave, the polarity relationship between $i(t)$ and $i(t)$ is shown in Table 1. Fig.2 shows the propagation of initial current traveling wave generated by a fault at f_1 .

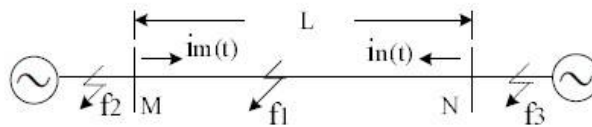


Fig 5: Fault of internal and external

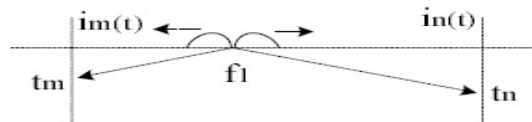


Fig 6: Propagation of initial current traveling wave [8]

We can clearly see from Table 1 if $i(t)$ and $i(t)$ have same polarity, the fault can be discriminated as internal to protected line; if $im(t)$ and $in(t)$ have opposite polarity, the fault can be discriminated as external.

Table I: Polarity relationship of internal or external fault

Fault Type	Polarity		Relationship	
	$im(t)$	$in(t)$		
Internal(F_1)	+	+	Same	
	-	-	Same	
External	F_2	+	-	Opposite
		-	+	Opposite
	F_3	+	-	Opposite
		-	+	Opposite

According to modal maximum of wavelet transform and singularity detection theory, the break point of traveling wave signal is in accordance with the modal maximum of signal. Therefore, through detecting modal maximum of traveling wave signal, fault information can be extracted. For the protected line MN, Fig.6 and Fig.7 show modal current and modal maxima of transient current traveling wave seen at end M and N for internal or external fault respectively.

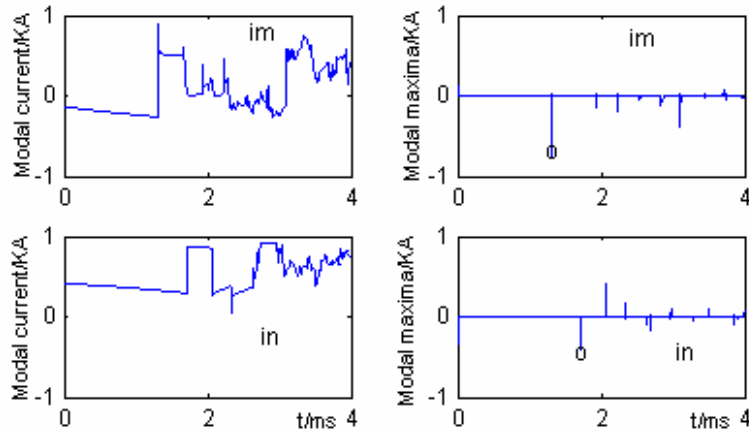


Fig 6: Current and modal maxima of internal fault [4]

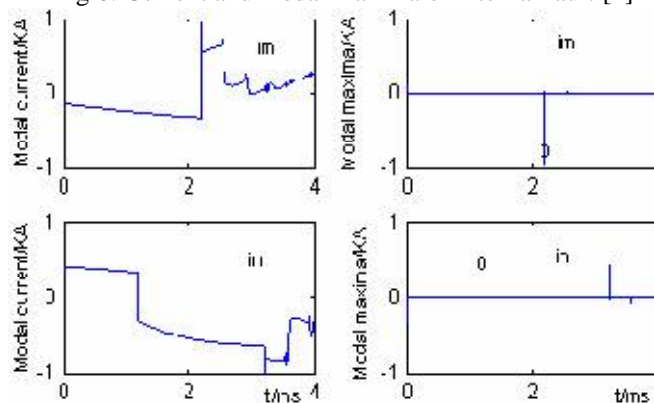


Fig 7: Current and modal maxima of external fault [4]

From Fig.6, we can see: if a fault is internal, at end M and N the polarity of the initial modal maximum of wavelet transform is the same. But Fig.7 shows: when an external fault occurs, their polarity of initial modal maximum is the opposite. Therefore, according to the polarity relationship between initial modal maximum of current traveling wave at two ends, the traveling waveprotection algorithm can fast discern whether a fault is internal or not.

IV. SIMULATION RESULTS

Recorded data from a real system was not available to test the performance of the relay algorithm. Instead, test waveforms were generated through PSCAD EMTDC/MATLAB simulation and programming. The 500kV three-phase power system shown in

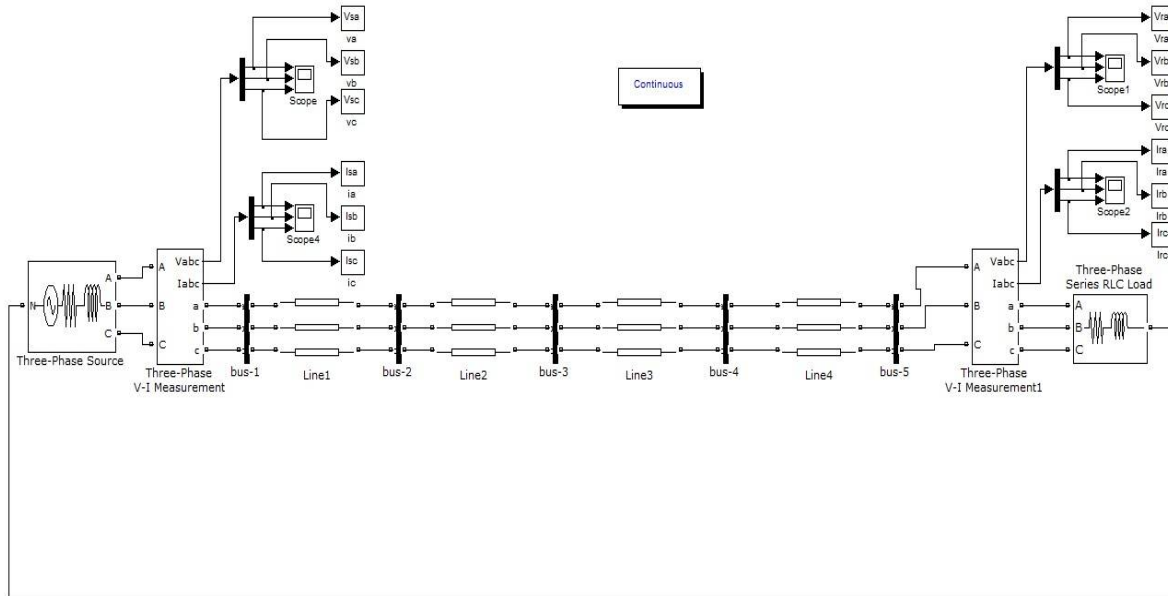


Fig 8 Line configuration of 500 kV system

Line configuration data:

Height of outer conductors, $h_c = 28.956$ m

Height of centre conductor, $h_c + h_o = 38.648$ m

Horizontal space between phases, $x_c = 6.71$ m

Conductor radius, $r = 1.65354 \times 10^{-2}$ m

No. of conductor in a bundle $N = 3$

Line parameter:

Conductor DC resistance = 0.0489 Y/km

Calculation of voltages, currents, distances to fault and relay signal-

The proposed methodology has been tested by implementing it on a 500 kV test system with different types of faults at different locations on a transmission line. The results obtained using proposed method, have been compared with the reference [1].

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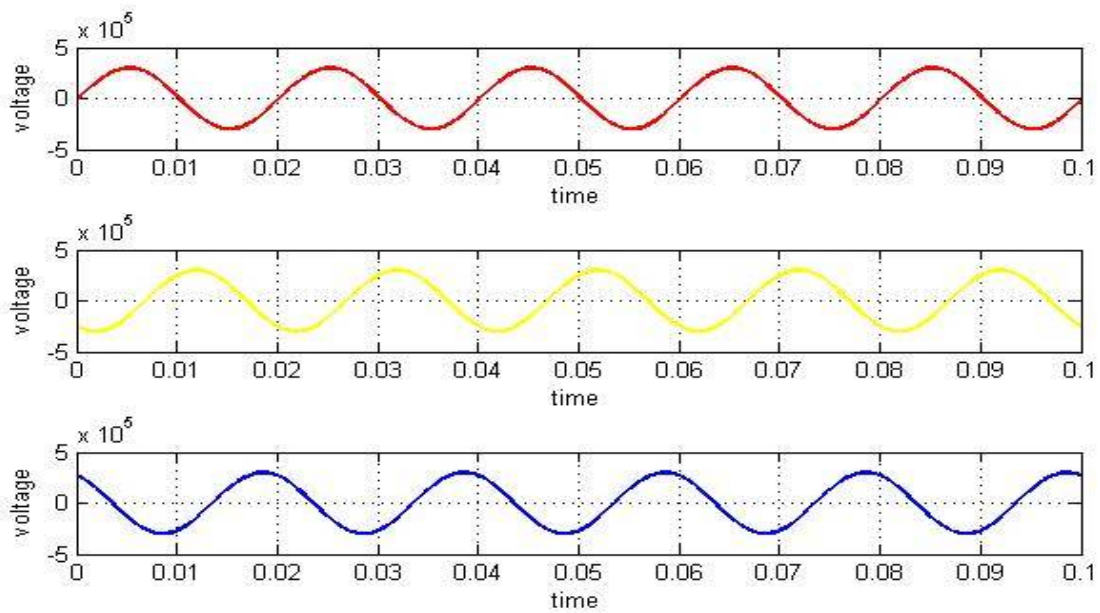


Fig 9 post-fault voltages

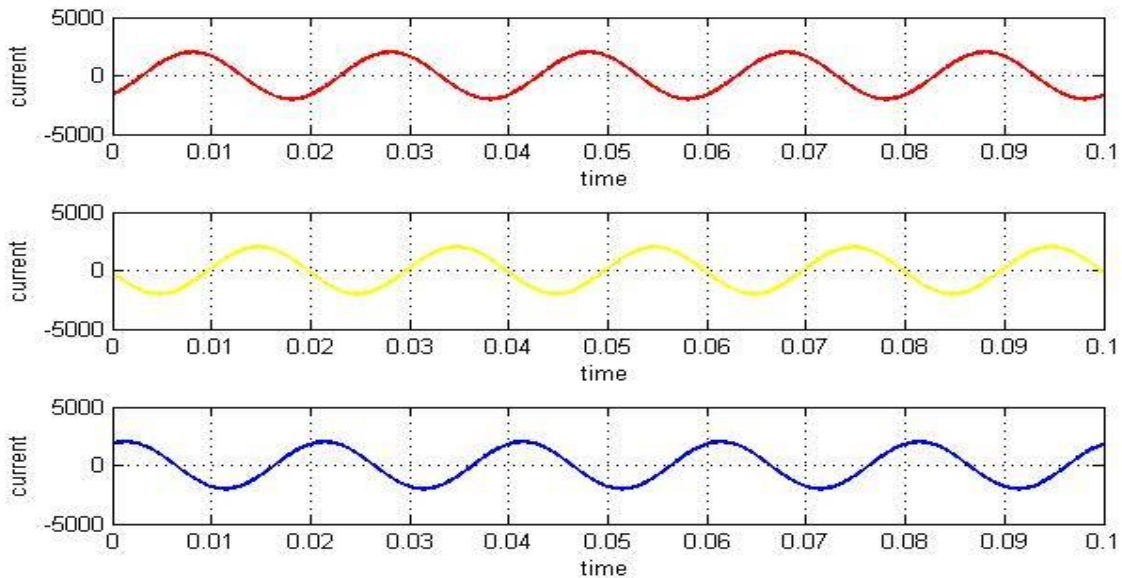


Fig 10 post-fault currents

When 3-ph to ground fault occurs at a distance of 525 km away from the relay location at an inception angle 90°, the results obtained using MATLAB programming are as below; Post-fault phase voltages and currents for all phases

High frequency forward and backward voltage travelling wave are-

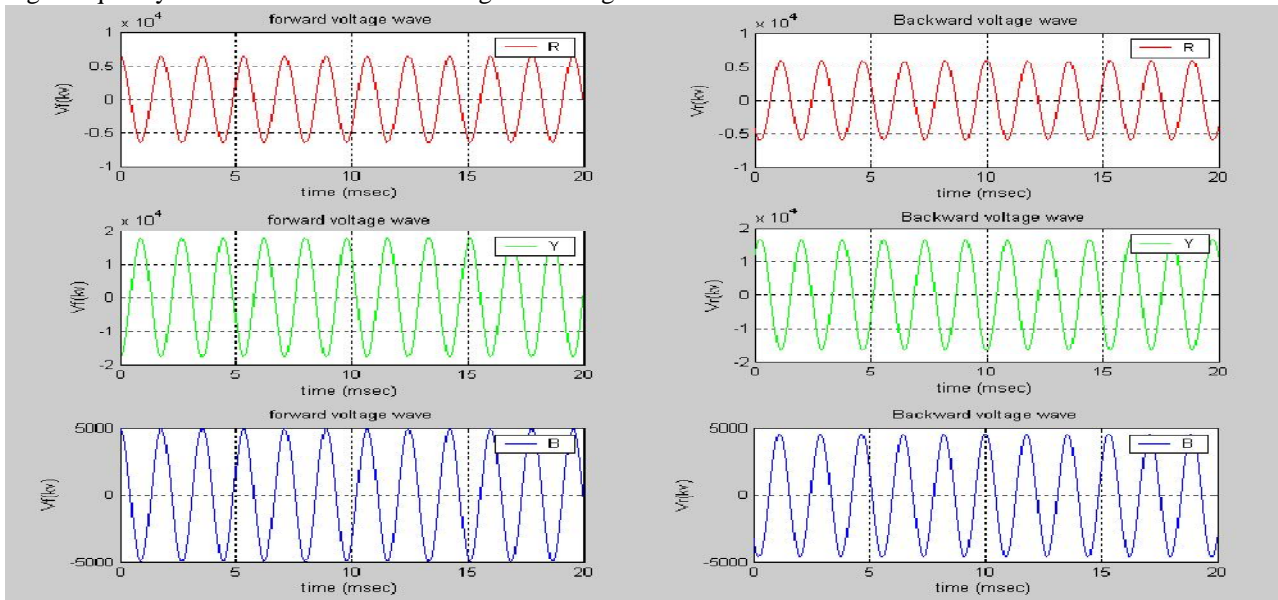


Fig 11 Voltage travelling waves

High frequency forward and backward currents travelling wave are-

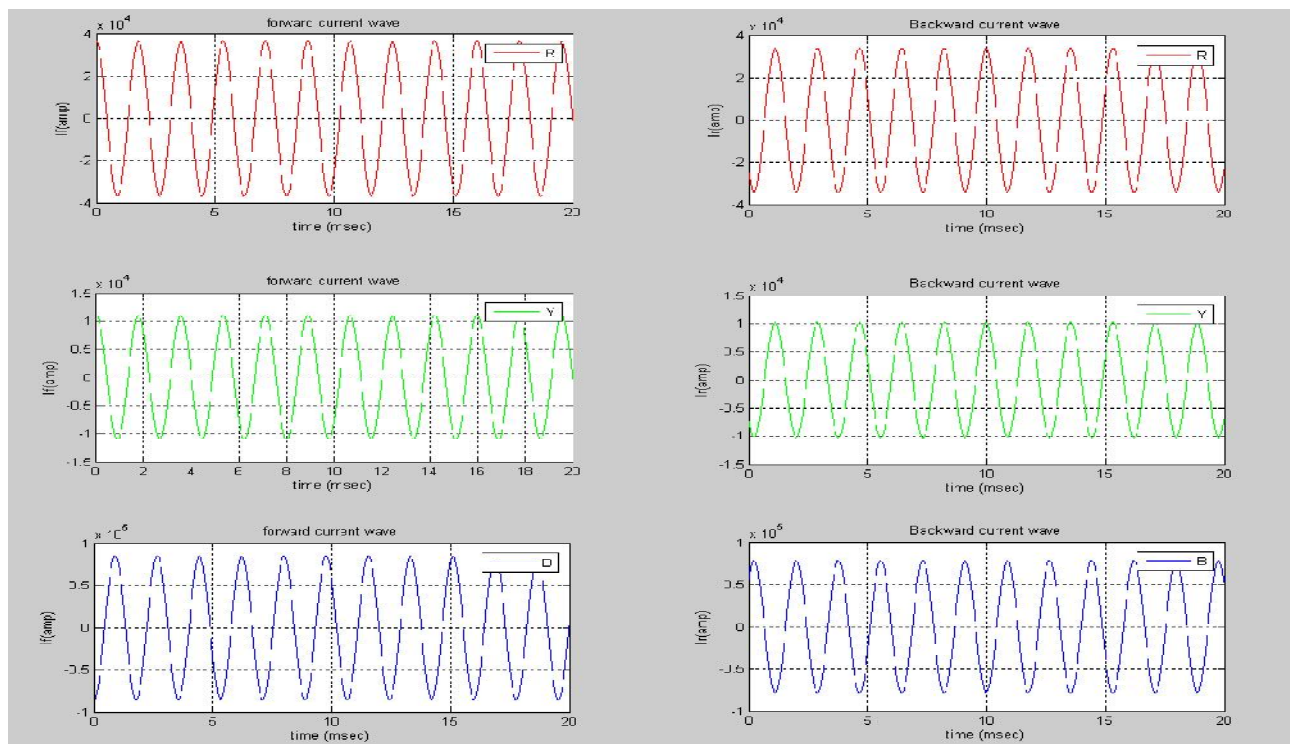


Fig 12 Current travelling waves

Fig.8 used for the simulations. The transmission lines are assumed to be uniformly distributed along its length, fully transposed and frequency dependent. The propagation velocity of travelling wave is $v_p = 3 \text{ m/s}$.

The simulation results are shown in Table II . Fig.6 shows modal current and modal maximum for internal phase A to ground fault at f1 away from end M 90Km, fault inception angle 90° and fault-grounded resistance 50Ω . Fig.7 shows modal current and modal maximum for external phase A to ground fault at f4.

Table II: Simulation results for internal a-g faults at different fault positions

Fault Position(Km)	Polarity	Operation Performance	End M Location(Km)
525	Same	Trip	524.900
220	Same	Trip	220.00638
195	Same	Trip	194.9

From Table II and III we can see that the traveling wave protection and location algorithm can correctly operate for the internal and external faults, furthermore, the accuracy of fault location is very high for an internal fault, except that a single phase to ground fault occurs with a zero voltage inception angle.

Table III: Simulation results for internal a-g faults with different fault grounded resistances (45km away from end m)

Resistance (Ω)	Polarity	Operation Performance	End M Location(Km)
0	Same	Trip	44.978
50	Same	Trip	44.978
300	Same	Trip	44.978

V. CONCLUSION

Fault can be detected using both BERGERONS EQUATION and Polarity comparison method. In BERGERONS EQUATION method a non-zero value of $\epsilon_1(t)$ and $\epsilon_2(t)$ effectively signifies that internal fault is exist. In Polarity comparison method simply comparing the traveling wave polarity fault is detected. Fault location can be found out by finding the traveling time of wave to relay location 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, Compensated transmission line, Lines with T branches, The line containing cable sections and overhead line

The algorithm was presented by considering two possible situations. In the first one, the data-transmission latency has a small or negligible variability and the algorithm provides the fault point estimation as the classical traveling-wave-based methods do. In the second situation, the data-transmission latency has large variability and the proposed algorithm estimates the search field of the fault. To do so, several measurements of the data-transmission latency are continuously taken to compute reliable confidence intervals of the fault location.

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