Traveling Wave Fault Location Detection Technique for High Voltage Transmission Lines

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TRAVELING WAVE FAULT LOCATION DETECTION TECHNIQUE FOR HIGH VOLTAGE TRANSMISSION LINES

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***Abstract* – The exact pinpointing of faults is an essential aspect of the electrical network services. Optimized location of faults will minimize downtime, enhance reliability, and be more cost-effective. Whenever a fault emerges, a disruption in the voltage and current is sent approximately at the speed of light in either trajectory. This disruption is known as the traveling wave, which may be utilized to pinpoint fault locations. The utilization of the traveling wave concept to pinpoint faults is becoming essential in attempts to improve precision. This paper presents a traveling wave algorithm centered on transmitted forward and backward electromagnetic waves induced when a fault appears in the transmission overhead line. The details found in the traveling surge can estimate the location where the fault emerged by measuring the initial traveling surgeon's periods of the two termination points of the line. The aim is to detect and pinpoint the fault's location utilizing the data collected of the electromagnetic waves produced by current traveling waves. The research is focused on the current and voltage signal analysis. The method has been designed using MATLAB/SIMULINK, where several case studies of the traveling wave fault location detection were analyzed.**

Keywords – fault location, electromagnetic surges, electrical fault, transmission line, traveling wave.

I. INTRODUCTION

Transmission lines are utilized to transport electrical power from power plants to different distribution substations. Electricity is distributed in voltage and current waves [1] from one termination to the other. Several faults could contribute to power loss: including system breakdown, storms, vegetation, and many more. Entities and businesses should investigate the causes for power outages in power systems [2]. A fault is possible due to certain uncontrollable variables in the electricity network. The various forms of fault causes [3] have common fault characteristics. The faults' causes may be established by an inspection of the fault function, which is useful for troubleshooting and fault-clearing after the fault occurred. Serious damage may occur if faults are not identified immediately, resulting in a complete system shutdown [4].

An effective and optimal safety scheme is necessary to remove the faulty segment of the power lines. Protective devices are mounted at different overhead transmission line locations to monitor the power system in case of the occurrence of faults. This ensures that the fault is detected and the system is isolated from the faulty portion of the network [5].

Traveling wave techniques [6] are now substituting conventional fault location detection methods in a power system. The traveling wave approach benefits are to minimize the fault clearance time, define the fault position, additional damage prevention, and improve the safety aspects. Clearing time is the amount of time the circuit safety system requires to clear the fault. When a fault is initiated, the fault will damage the switchgear until an upstream protection defensive system [7], such as a circuit breaker opens the faulted circuit and cuts-off the power supply; thus, isolates the fault.

Traveling waves are correlated with electromagnetic waves' movement originating from fault conditions in power lines and lightning or changing processes in the electricity network. An unexpected and substantial change in voltage at one position along the transmitting voltage line contributes to creating electromagnetic waves [8] that spread in different directions from that location. The electromagnetic waves may be categorized into voltage, and current waves integrated from the magnetic field traveling at limitless speed along the transmission line [9].

This paper aims to analyze fault location detection in a power system that relies on multiple organizations' traveling wave techniques today. The traveling wave technique is determined based on the voltage and current measurements. The currents and voltages generate electromagnetic surges that travel to the overhead transmission line buses. These electromagnetic surges arriving times are then used to estimate the location of the fault. Different scenarios will be simulated using MATLAB/SIMULINK software.

II. TRAVELING WAVE THEORY

The transmission line interruption occurs as a transition to the constant state power equation and transmits the traveling wave in both directions. Figure 1 indicates a small segment of the overhead transmission line length. As a transmission system failure emerges, a traveling wave generated from faulty currents and voltages is produced [10]. The corresponding circuit of a section employing a two-conductor overhead transmission line of distance Δx. The circuit consists of the line's resistance R, inductance L, conductance G, and capacitance C per unit of the line's total distance.

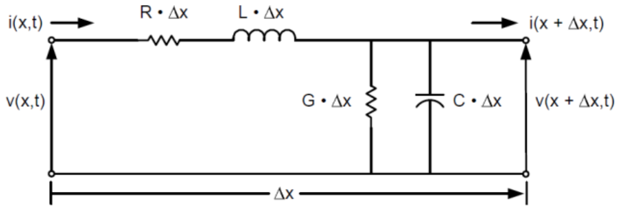

Fig. 1: Single-phase transmission line [10].

The electromagnetic wave flowing through the system produces a traveling wave of a voltage drop in the magnetic flux's positive direction.

$$\frac{dV}{dx} = R_i + L\frac{di}{dt} \tag{1}$$

The expression for the current traveling wave can be attained utilizing the capacitance and the leakage's conductivity.

$$\frac{di}{dx} = VG + C\frac{dV}{dt} \tag{2}$$

Below are the general solution formulas by taking Laplace transforms of equations (1) and (2) with regards to the time parameter *t*.

$$Vx = VF + IFZc2\ e \propto xej\ \omega t + \beta x + VF - IFZc2\ e{-}\propto xe - j\ \omega t + \beta x \tag{3}$$

$$Ix = \left(\frac{VF/Zc{+}IF}{2}\right) e\alpha xej\ (wt + \beta x) - \left(\frac{VF/Zc{-}IF}{2}\right)\ e - \alpha xe - j\ (wt + \beta x) \tag{4}$$

The traveling wave may be generated from the fault position at any point of the line at distance *X* by using equations (3) and (4), where *Vf* and *If* are the fault voltage and current and α and β are the decreasing constant and phase constant, respectively.

A. Forward and Backward of the Traveling Waves

The traveling wave generated is composed of two components, as indicated in Figure 2. This is also seen in equations (3) and equation (4). The aspect descends from the line's transmitting point to its receiving point.

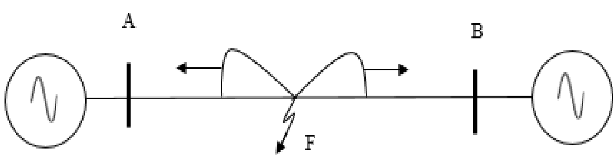

Fig. 2: Propagation of electromagnetic waves due to a fault [11].

These two components are based on the following factors: time *(t)* and distance *(X)*.

$$Vx\ =\ Vf\ +\ Vr \tag{5}$$

Where,

$$Vf\ = \left(\frac{VF+\ ZcIF}{2}\right) e\alpha xej\ (wt + \beta x) \tag{6}$$

Equation (6) is used to obtain the forward travel wave of the voltage.

The reflected travel wave [12] of the voltage can be obtained by using the equation (7):

$$Vr = \left(\frac{VF-\ ZcIF}{2}\right) e - \alpha xe - j\ (wt + \beta x) \tag{7}$$

These equations are significant to the equations used to derive the elements of the current traveling wave.

$$Ix\ =\ If -\ Ir \tag{8}$$

Where,

$$If = \left(\frac{\mathrm{VF/Zc{+}IF}}{2}\right)\ e\alpha xej\ (wt + \beta x) \tag{9}$$

Equation (9) is used to obtain the forward travel wave of the current, where equation (10) is used to calculate the reflected travel wave of the current [13].

$$Ir = \left(\frac{VF/Zc{-}IF}{2}\right) e - \alpha xe - j\ (wt + \beta x) \tag{10}$$

B. Reflection and Refraction of Traveling Waves

The traveling wave propagates through the power line and experiences distortions caused by electrical transformers, generators, and circuit breakers [14]. When a traveling wave stops at a location where the impedance instantly varies, the wave is partially reflected and partly refracted. Distortions are typically caused by the loss of electrical equipment and line cable intersections. Self-governing waves interacting across a line will merge to have varying voltage and current levels at the gathering location in conjunction with their polarity [15].

It is possible to execute a traveling wave direction algorithm. Forward current and voltage waves [16] are granted the very same polarity. If the wave is transmitted in the opposite direction, the resulting current and voltage waves are granted different polarities. Figure 3 describes the phenomena of reflection and refraction of the traveling wave based on Bewley's Lattice Principle. The figure explains the flow of traveling waves generated at a fault position *X* km from bus A on a transmission line that is *X* km in length.

The occurring wave's overall intensity is divided between the reflected and the refracted waves for any distortion. The phenomenon continues until the traveling waves exhaust all their momentum and their accelerations become insignificant [17].

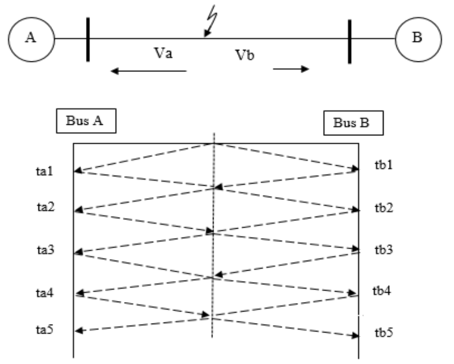

Fig. 3: Bewley's Lattice Principle diagram [16].

III. Traveling Wave Fault Location Techniques

A. Single-Ended Fault Location Approach

The single-ended fault pinpointing approach [18] utilizes a traveling wave that involves a fault locator unit positioned at one bus of the overhead power line's termination. Such an approach reduces the necessity for coordination between two buses. Thus, it reduces the cost where two fault locator units are required as with the double-ended approaches [19]. This single-ended approach allows for the emergence of the original traveling surge triggered by a fault on the overhead power line as well as for the reflection of the original surge to be accurately detected at the position of the fault.

As a fault emerges on transmission lines, voltage and current traveling surges are formed that scatter in opposite directions from the fault to the buses. If such traveling waves reach the buses (presuming a complete reflecting element at the buses), they are transmitted back to the fault region. When they reach the fault region, a portion of the traveling surge will return to one termination, and a portion will be transferred to the other end. The operation progresses until the waveform is depleted. Traveling waves are represented in terms of voltage and current by the forward, f_1, and backward, f_2 [20].

$$v(x,t) = f_1\left(t - \frac{x}{c}\right) + f_2\left(t + \frac{x}{c}\right) \tag{11}$$

$$i(x,t) = \frac{1}{Z_0} f_1\left(t - \frac{x}{c}\right) - \frac{1}{Z_0} f_2\left(t + \frac{x}{c}\right) \tag{12}$$

Where c is the surge transmitting speed, Z_0 is the normal impedance of the line, and X is the distance of the wave reflected from the fault destination. The forward, f_1, and backward, f_2, traveling surges, can be further expressed as:

$$f_1 = v(x,t) + Z_0 i(x,t) \tag{13}$$

$$f_2 = v(x,t) + Z_0 i(x,t) \tag{14}$$

According to Figure 3, by considering bus A; if the average time amongst the arrival of the forward surge, *ta1*, and that of the backward surge, *ta5*, is achieved, the location to the fault from bus A can be determined by making use of equation (15) [21].

$$d = \frac{ct}{2} \tag{15}$$

Where c is the speed of the traveling surge and t the period.

B. Double-Ended Fault Location Approach

As illustrated in Figure 3, the double-ended fault location principle is being used to develop the most visible and adaptable traveling wave, and it has been adopted for fault location and field equipment protection. The double-ended location approach is more complex and costly than the single-ended fault location approach. This approach involves utilizing numerous travel wave recording devices on separate buses and a signal relay for communication to locate faults on the transmission line [22]. This approach involves measuring the initial travel surge triggered by a fault on either bus and employing the time delay to measure the fault's distance. Double-ended fault location techniques are more precise, although the two buses need data. Data on both buses must be obtained before the method can be used. However, the single-ended location method [23] is recommended since it requires a single device for each line, and a communication connection is not required. Figure 3 illustrates the progression of waves to bus A and B during a fault state on a transmission overhead line.

The equation of the double-ended fault location technique is presented by:

$$X = \frac{1}{2}[L + v\tau(t_a - t_b)] \tag{16}$$

L represents the length of the overhead power line, v is the travel wave speed, τ is the inverse of the sampling rate, and *ta* and *tb* are the original travel wave's arrival times due to their fault corresponding buses.

IV. Methodology for Fault Location Estimation

The response duration will be calculated during the emergence of the surge generated by the fault, and the corresponding reflected surge. This is dependent on high-frequency signals to locate the fault in the power system. This is considerably easy to execute; however, the difficulty begins in detecting the reflected signals that travel from the bus to the fault and backward. The approach that may pinpoint the targeted pulse is centered on a self-correlation strategy [14].

Self-correlation governs if the traveling wave experiences match and may be utilized to pinpoint when the redirected waveform traveling wave occurs. A segment of the observed pulse is retained and employed as a guide to applying such a method [24].

Overhead transmission lines are designed to run at traditional electricity grid frequencies of 50 or 60 Hz. The paper's design simulation will be conducted at a frequency of 50 Hz, which is the standard frequency in South Africa and many other countries. This research suggests a methodology that measures each increase's comparative distance in the current signal of the existing reflecting areas in the power system. From this segment, the fault and the position of the fault can be located. The fault location detection algorithm was simulated using MATLAB/SIMULINK software to obtain the results.

V. DOUBLE-ENDED FAULT WAVEFORM COMMUNICATION

The travel wave approach solution calculates the exact time differential at the original surge of the current traveling surge at either endpoint of the power line to reach the buses. It is, therefore, appropriate to develop a communication network capable of responding to the requirement for the speed and absolute co-occurrence at either end of the line [25]. Symmetric monitoring at both terminations of the overhead power line has proven a possibility of advancing the global positioning system (GPS). The GPS monitoring system and the wireless communication devices [26] are mounted on each transmission line's termination to guarantee the information is processed instantaneously. To achieve the speed sampling for the traveling wave signals, GPS integrated sampling engineering can provide a higher level of simultaneous sampling where the average error is below one microsecond [27].

The use of a GPS can also be substituted by differential relay-to-relay communication [28]. The relays use the traveling wave data sent to the buses without altering the differential element's functionality. These relays utilize a 64 kbps cable [29] to share current signal times, utilize the data to determine the fault position, and allowing the findings to be available at both relays.

The use of fiber Optic Ground Wire (OPGW) [30] is another communication technique used between buses should an electrical fault occur. The OPGW is not only used for communication purposes but also for protecting the three-phase conductors. Data are transported using optic-fiber [31] integrated within the OPGW for the buses to communicate with each other.

VI. DOUBLE-ENDED FAULT LOCATION DESIGN APPLICATION

Traveling waves for fault location applications typically observe transients in voltage and current quantities in electrical transmission line buses. Traveling waves are generated throughout the network due to fault initiation. The development of the methodology is illustrated in Figure 4.

During phase one, a fault occurs on the transmission line, resulting in traveling waves caused by electromagnetic surges. The wave classification is performed in phase two. This is obtained by comparing normal 50 Hz waves with waves caused by higher frequencies. In phase three, the initial traveling wave time arriving at bus A and bus B are $ta1$ and $tb1$, respectively. The GPS estimates the fault location based on the arrival times at both buses. The exact time is obtained and used to detect the fault's exact location in phase four, as shown in Figure 4.

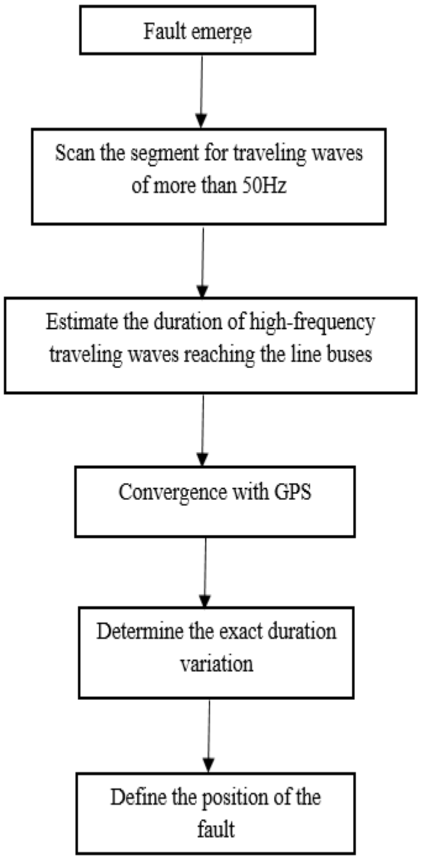

Fig. 4: Double-ended Traveling Wave flow chart.

VII. MATLAB SIMULINK MODEL

This section presents a three-phase power system design of a high voltage transmission overhead line utilizing MATLAB/SIMULINK. Figure 5 illustrates the schematic diagram of the designed simulation model. The system is designed by applying typical transmission line parameters to produce highly precise findings while applying the suggested strategy on a long overhead power line.

The three-phase model's network structure is an overhead transmission line of 400 kV, 50 Hz, and 300 km. It comprises voltage and current measurements, circuit breakers, transmission lines, and loads. The primary objective of the overhead power lines is to provide the loads with three-phase power. The electricity produced by the generators is delivered to the loads through the power transmission system. The circuit breakers are switchgear that connects and disconnects the network's electrical interaction and prevents current from flowing through the network.

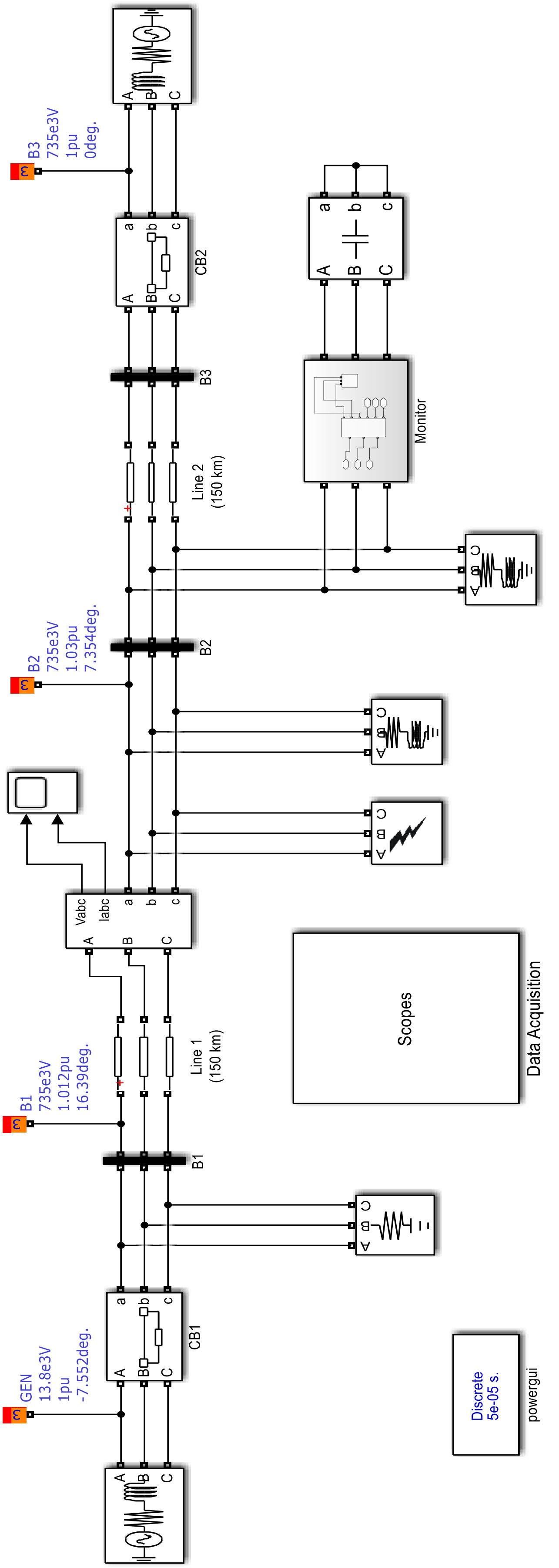

Fig. 5: Transmission line fault position design centered on traveling surge method.

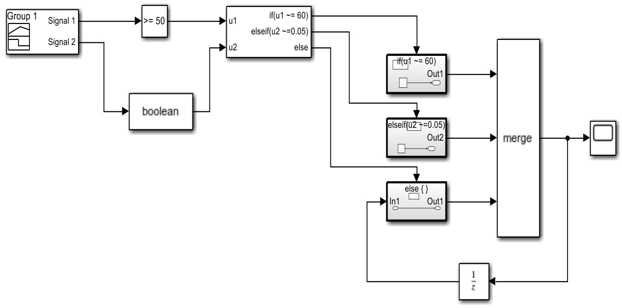

Fig. 6: Traveling wave monitoring device design in MATLAB/SIMULINK.

VIII. Simulation Results and Discussion

A. Traveling surge due to L-L fault

In Figure 7, an L-L fault is simulated at 200 km on a 300 km transmission line at 50 Hz between phase A and phase C from B1 to B3 discarding B2, for this simulation only, as illustrated in Figure 5. In Figure 7, it can be seen that the current magnitude of phase *A* and phase *C* is greater than phase B. High magnetic fields flowing through the transmission line are produced by the faulty phases, introducing the traveling waves. These traveling waves are then used to pinpoint the transmission line's fault location.

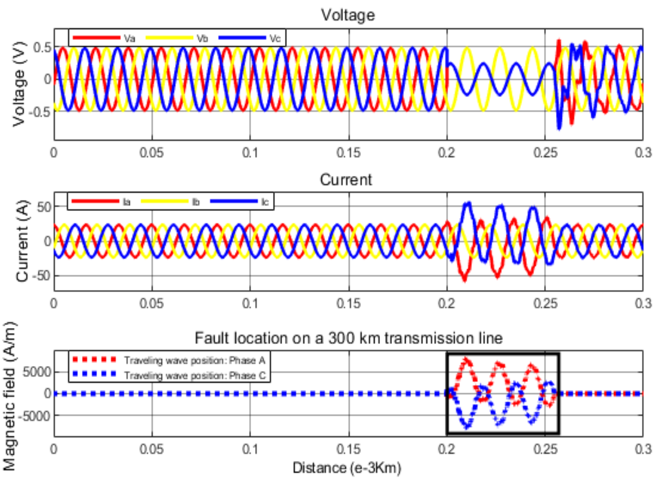

Fig. 7: Forward and backward traveling waves during an asymmetrical fault.

B. Traveling surge due to L-G fault

Figure 8 illustrates the voltages and currents waveform when a phase-to-ground fault was modeled at 50 km of transmission line 1 (phase *A*) approaching *B1* and *B2*. In Figure 8, it can be observed that the current magnitude of phase *A* is greater than the other two phases. High magnetic fields flowing through the line are produced by the faulty phase, which introduces the traveling waves. These traveling waves are then used to pinpoint the transmission line's fault location.

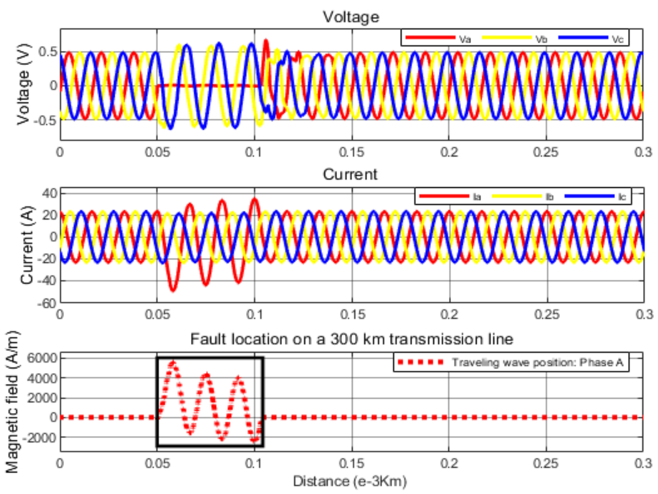

Fig. 8: Forward and backward traveling waves during an asymmetrical fault.

C. *Traveling surge due to LL-G fault*

In Figure 9, an LL-G fault is simulated at 100 km distant from *B2*. The current for both phase *A* and phase *B* has increased in magnitude due to the fault. Because of the traveling wave approaching *B2* and *B3* of transmission line 2, it can be observed that higher magnetic fields flowing through line 2 are generated by the faulty phases. These magnetic fields are then converted into traveling waves, which are utilized to pinpoint the fault position on the overhead power line. Since the fault occurs between *B2* and *B3*, the traveling wave will move backward and forward between these two buses.

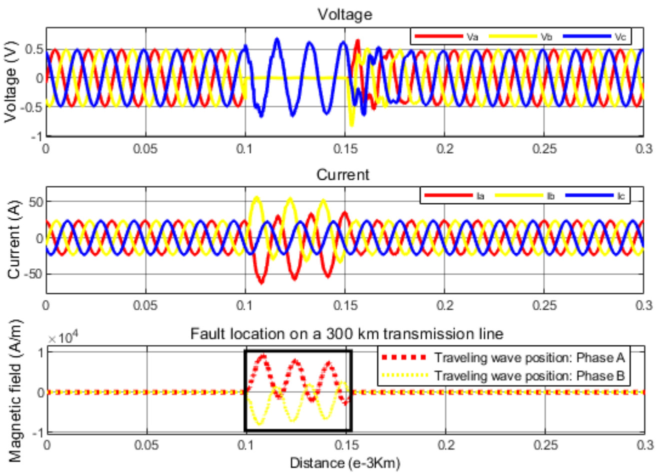

Fig. 9: Forward and backward traveling waves during an asymmetrical fault.

D. *Traveling surge due to LLL-G fault*

The simulation in Figure 10 is exposed to a three-phase to ground fault in the transmission line between B1 and B2. The traveling wave is observed at a starting distance of 150 km due to the rapid rise in the current of all three phases caused by the fault. Faulty traveling wave propagates to both buses of the overhead transmission line. The equipment at both buses can then locate the position of the fault by utilizing the traveling waves data.

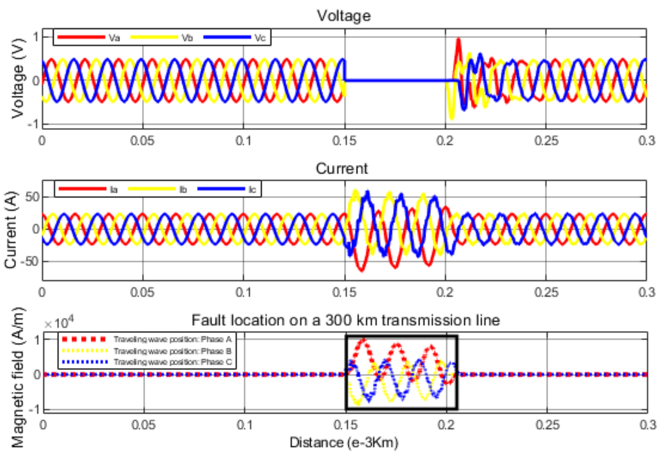

Fig.10: Forward and backward traveling waves during a symmetrical fault.

IX. CONCLUSION

This research paper describes a double-ended fault location detection strategy of the traveling wave system to pinpoint the fault position when a transmission line fault is detected. MATLAB/SIMULINK software was utilized to perform several modeling simulations and scenarios, demonstrating accuracy and reliability. This technique can measure the position where the fault occurred using the forward and backward approach towards both ends of the transmission line. The transmission line parameters, such as the resistance, the reflection, and refraction of the conductor, do not have a huge impact on the proposed technique and the advantage of high precision.

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BIOGRAPHY

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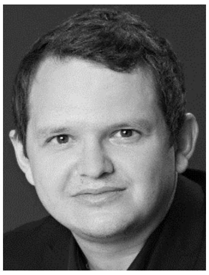

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