School of Information Technology and Engineering at the ADA University

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DETERMINING THE LOCATION OF A 220 KV OVERHEAD LINE FAULT USING THE WAVE (TRAVELING WAVE) METHOD

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THESIS ACCEPTANCE

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ABSTRACT

This thesis presents a procedure for the accurate computation of 220 kV overhead transmission line fault location using the traveling wave (TW) method of fault location. Compared to traditional impedance-based methods with high sensitivity to fault resistance, load flow, and system parameters, the traveling wave method is highly accurate based on the physical electromagnetic transients propagation time.

The traveling wave technique depends on the observation of the high-frequency voltage and current transients created during fault, traveling along the line nearly at light speed. The accurate location of a fault can be computed by measuring the time-of-arrival of the first wavefronts at the line terminals. Essential to such precise high accuracy is sub-microsecond resolution offered by cutting-edge GPS time synchronization and MHz-range high-frequency data sampling that avoid the limitations of earlier TW systems.

The research makes use of the two-ended fault location technique, which sets the first wave front arrival times at both local (tL) and remote (tR) line ends.

The core of the research is the Simulink model developed in MATLAB to simulate 220 kV transmission line using the distributed parameter model.

This model has a specific Traveling Wave Fault Locator (TWFL) subsystem for calculating propagation velocity from line inductance and capacitance and end fault distance. This simulation confirms the high accuracy of the principle, where it is able to identify faults with a precision of several hundred meters and contribute towards quicker restoration of systems and lower outage duration. The work acknowledges significant challenges, including expense and complexity of the high-speed data acquisition equipment required, and possibility of signal noise and wave reflection leading to inaccuracy. Future research directions, like combining machine learning with hybrid TW-impedance schemes, are mentioned as one possible means of further enhancing this significant power system protection technology's reliability and application.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
ABC	Three-Phase Fault (Phases A, B, and C)
AB-G	Double Line-to-Ground Fault between Phases A, B, and Ground
A-G	Single Line-to-Ground Fault on Phase A
AI	Artificial Intelligence
CVT	Capacitive Voltage Transformer
CCVT	Coupling Capacitor Voltage Transformer
CT	Current Transformer
DFR	Digital Fault Recorder
EMTR	Electromagnetic Transient Recorder
EHV	Extra High Voltage
GPS	Global Positioning System
HVDC	High Voltage Direct Current
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
km	Kilometer
L	Inductance per Unit Length
ML	Machine Learning
NCIT	Non-Conventional Instrument Transformer
OHL	Overhead Line
OPEX	Operational Expenditure
PTP	Precision Time Protocol
pu	Per Unit (normalized measurement system)
RLC	Resistor–Inductor–Capacitor
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
TW	Traveling Wave
TWFL	Traveling Wave Fault Locator
V	Voltage
VT	Voltage Transformer
WAMS	Wide Area Monitoring System

CHAPTER ONE:
INTRODUCTION

Exact and swift fault location on high-voltage overhead transmission lines is very important for the consistency, safety, and reliability of power supply. The traveling wave technique is one of the most modern and most precise techniques, most convenient for 220 kV overhead transmission lines. This method exploits the high-frequency voltage and current transients, so-called traveling waves, which are produced when a fault on a line is established. The waves propagate along the transmission conductors at almost the speed of light and are sensed at one or both ends of the line by high-speed sensors and synchronized measurement systems, most commonly assisted by GPS timing. By measuring the differences in the arrival times of these waveforms, a good estimate of the fault distance from the point of measurement can be determined.

The traveling wave technique holds more advantage over traditional impedance-based techniques, particularly under fault conditions with high fault resistance or with varying loading conditions, which have the effect of complicating the traditional techniques. It is accurate to millisecond order in detecting faults and is relatively insensitive to line parameters such as load flow, type of fault, and resistance. It is especially suitable for high-voltage, long-haul lines such as 220 kV lines, where small response time and high precision are particularly valuable. Its realization, however, is not without difficulties. Ultra-fast high-speed data acquisition hardware, secure synchronization, and advanced signal processing algorithms render realization costly and technologically demanding.

Furthermore, noise, line discontinuity reflections, and transient attenuation may lead to interpretation errors, and high-end filtering and intelligent processing software such as artificial intelligence (AI) and machine learning (ML) must be used to improve reliability.

Advances in digital signal processing, GPS technology, and AI immersion have also enhanced the efficiency of the traveling wave method to make it more applicable to modern power utilities dedicated to grid modernization. The current paper is a review of the theoretical background, technical realization, and performance advantage of the traveling wave technique in fault location in 220 kV overhead transmission lines with its paramount importance in the future smart and resilient power system infrastructure.

1.1. Problem Statement

The 220 kV overhead transmission lines are key components of the new grid, which carry out the bulk power transmission over long distances. They are always exposed to external effects, such as lightning, environmental loads, and transient faults, causing interruption of service. The fault location accuracy and speed are the current challenges for the utility operator.

The traditional impedance-based fault location techniques typically have some weaknesses:

Low Accuracy: The fault location errors of a few kilometers can be attributed to the disturbances created by load flow change, tower footing resistance, fault resistance, and non-uniform line sections.

Operational Delay: Application of these less accurate methods consumes more time communication along the lines, which contributes to System Average Interruption Duration Index (SAIDI) considerably and increases the repair cost.

Incapacity to Handle Transient Occurrences: They cannot identify faults in complex or changing transient fault conditions.

Hence, a solution that is desperately needed is an extremely accurate, reliable, and fast fault location technique that can be implemented on long-distance, high-voltage transmission lines. This study is aimed at solving the specific problem of inferring and determining the use of the Traveling Wave (Surge) Method to give sub-span-level accuracy in a fast manner to determine the physical location of transient faults on a 220 kV overhead power transmission line.

1.2. Definition of Terms

The following are the primary technical terms defined to shed light and background on this study:

220 kV Overhead Line: A high-voltage electrical power transmission line, suspended by steel towers, with a nominal phase-to-phase voltage of 220 kilovolts.

Fault Location: The process of precisely calculating the distance from a detected monitoring terminal to the point of a short circuit or ground fault along the transmission line.

Traveling Wave Method (Surge Method): A high-frequency fault location technique which determines the fault location by measurement of the time difference between the instant the electromagnetic wave is generated at the fault point and the instant that it reaches as a reflection at one or both ends of the line.

Traveling Wave (Surge): A high-frequency voltage and current disturbance with a steep front resulting from the sudden alteration of the electrical conditions of the line, i.e., fault occurrence or line switching. It propagates on the line at a velocity almost equal to the velocity of light.

Velocity of Propagation (Wave Speed): The rate at which the traveling wave moves on the conductor, relying primarily on the characteristic inductance and capacitance of the line. In overhead lines, it would typically be between 280 and 300 meters per microsecond.

Digital Fault Recorder (DFR): Synchronized high-speed data acquisition devices mounted in substations for recording and time-stamping the arrival of high-frequency traveling waves with nanosecond precision.

1.3. Significance of the Study

The outcome of this research is anticipated to make important practical and educational contributions to the operation and maintenance of high-voltage transmission systems:

Improved Grid Reliability: By greatly decreasing the time consumed to precisely locate a fault, the research directly minimizes outage duration, and consequently improves the System Average Interruption Frequency Index (SAIFI) and SAIDI measures and overall grid stability.

Operational Efficiency and Cost Saving: Sub-span-level accuracy offered by the traveling wave method minimizes physical line patrolling to a great extent. This translates to lower operational expenditure (OPEX), faster mobilization of the restoration crew, and smaller environmental impact.

Progress in Protection Engineering: The validation of the process provides a good platform for utility companies that are in the process of planning the upgrading of their protection and monitoring systems for the implementation of state-of-the-art fault location technology.

Contribution to Academia: The study provides a clear insight into wave propagation behavior on a 220 kV system with new knowledge and models toward high-frequency transient analysis in power system studies.

1.4.Scope of Study

The following limitations define the scope of this effort, setting the boundary of research findings:

Scope of Analysis (Modeling vs. Field): Topical derivation and simulation on power system analysis software (e.g., MATLAB or PSCAD) takes highest precedence. The research is limited in its ability to account for all the complexities and non-linear effects that occur in reality and encountered during physical implementation in the field.

Wave Attenuation and Noise: While the simulation represents simple wave propagation, it was not possible to simulate the very high attenuation, dispersion, and noise that high-frequency waves experience on very long lines, so much so that in practice it may be hard to assign accurate time-tags to wave front arrivals.

Hardware Complexity Exclusion: This paper does not enter into the intricate engineering design, the involved cost analysis, or the challenges in the precise clock synchronisation (e.g., GPS-synchronised timing) required for hardware implementation of the dual-ended traveling wave.

Fault Resistance Range: Even though the traveling wave method is better in the situation of high-resistance faults compared to impedance methods, the proposed work may not investigate as comprehensively the precision of location over the range of fault resistance values and angles of fault initiation.

CHAPTER TWO:
LITERATURE REVIEW

Fault location is a method of determining where exactly a fault occurs on a power system with the highest degree of accuracy. It is supported by fault locators—specialized equipment that employs fault-location algorithms to calculate the distance to the location of the fault. Such fault-location capabilities can be deployed on types of apparatus:

1. Microprocessor-based protective relays
2. Digital fault recorders (DFRs)
3. Stand-alone fault locators
4. Post-fault analysis software

Although fault locators and protective relays are similar in character, they are not alike in several significant aspects, such as:

1. Accuracy of fault location
2. Speed of fault detection
3. Delay in data transmission from remote locations
4. Duration of the data window used
5. Complexity of digital filtering and signal processing

While protective relays only sense and clear a faulted region, fault locating equipment will actually determine the location of the fault. Protective relays must respond very quickly to remove the faulty section and prevent further system disturbance. For this purpose, modern relays employ fast-measurement techniques and high-speed operation circuit breakers. Time of fault clearing is a principal factor—slow operation can lead to system instability, equipment maloperation, and disturbance to consumers. On the other hand, excessively fast protection can impair the security and selectivity of the protection system.

To meet the requirement for fast fault clearance, protection devices are often called upon to initiate a trip signal within less than a power frequency cycle (i.e., for a 50 Hz system, within 20 milliseconds).

Fault locators, however, are typically run offline and are used by skilled personnel for analytical purposes. Since their output is not time-critical, fault location calculations can take seconds or even minutes. These devices may utilize slower communication protocols such as SCADA or delayed transmission of data, unlike high-speed communications used in protection equipment. As fault location occurs offline, it becomes possible to select the optimum portion of the data window to improve accuracy. The window generally extends from the start of the fault until the fault is cleared, normally for about three cycles of the system frequency (60 or 50 Hz), longer than utilized by real-time protection.

Computational efficiency is more of a concern for protective relays, hence their algorithms must be fast and straightforward. Fault-location tools, however, are not subject to time constraints and may use more sophisticated approaches—e.g., DC component elimination to enable more accurate phasor analysis.

Of all the types of protective relays, distance relays come closest to fault locating. On occurrence of a fault in a pre-determined protection zone, the distance relay issues a trip to the circuit breaker with speed action. Two distance relays are typically installed at each end of a two-terminal transmission line and linked with pilot schemes. Through communication, both relays can alternate to trip the fault in the first protection zone.

But fault resistance can have significant influence on the behavior of distance relays—a phenomenon known as the reactance effect. It can cause relay misoperation for forward external faults or failure to trip for internal faults if the fault resistance is high. The phenomenon is especially characteristic in ground faults, which are the most common fault type on overhead transmission lines.

2.1. Theoretical Foundation and Evolution

Wave propagation method of fault location in extra-high-voltage transmission lines is a significant power system protection innovation. The method is based on electromagnetic wave propagation theory. During a fault occurring in a transmission line, it produces high-frequency voltage and current transients that are called traveling waves. These waves travel with almost the speed of light on the transmission line and reflect or refract at discontinuities such as faults, line ends, or junctions. By measuring the time these waves take to reach monitoring points and their pattern analysis, the fault position can be calculated exactly [6].

Historically, fault location methods began with simple impedance calculations. These use line impedance and voltage-current measurements to give an estimate of fault location. Though robust in the majority of cases, they are compromised by varying fault resistance, line load, and network complexity. As the power system size and complexity increased, the need for more timely and accurate fault detection means became apparent [7].

Traveling wave fault location was first proposed during the mid-20th century but not until the arrival of high-speed data capture and GPS time synchronization during the later 20th and early 21st centuries was it possible to have beneficial implementations. The early systems suffered from limited resolution and low sampling rates, but contemporary digital relays and advanced monitoring units now support microsecond-scale detection and processing [8].

The accuracy of wave detection has been greatly enhanced by GPS-based synchronization and high-frequency sampling in the MHz range. The following is an overview of the primary wave characteristics applicable to fault location [9]:

Table 2.0.1. An overview of the primary wave characteristics applicable to fault location.

Parameter	Typical Value	Importance in Fault Location
Propagation Speed	~300,000 km/s	Determines fault distance based on time delay
Frequency Range	10 kHz – 1 MHz	Requires high-frequency sensors
Time Resolution	< 1 μs	Enables accurate wave arrival detection
Signal Attenuation	Line-dependent	Affects detectability over long distances
Reflection Coefficients	Varies at discontinuities	Influences wave behavior at line terminations

Wave propagation physics is defined by telegrapher's equations that are partial differential current and voltage wave equations of transmission line. Distributed inductance, capacitance, and line resistance are considered in these equations. A number of analytical and numerical solutions to the equations have been researched thoroughly by scholars for improving the accuracy of fault location. [10].

2.2. Different types of Travelling wave methods

Power system disturbances like faults, switching events, and lightning generate rapid, high-magnitude surges of voltage and current. These surges, known as travelling waves, propagate along the transmission line. The travelling wave fault locator determines the distance to fault by measuring the time for the surge: to travel from the fault to the substation bus. Since 1950s several practical fault location methods have been proposed.

2.2.1. Type D (double ended) method

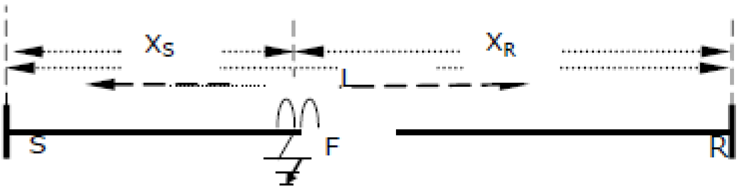

Fig. 2.1. Principle of Type D method

In Type D Method, the units at both ends of a line are synchronized in time and arrival time tags of fault generated surges are recorded. at both ends. The fault distance is determined measuring the difference of the arrival times.

$$X_S = \frac{(T_S - T_R) \cdot v + L}{2} \tag{2.1}$$

$$X_R = \frac{(T_R - T_S) \cdot v + L}{2} \tag{2.2}$$

Where, TS and TR are the absolute time of detecting the fault generated surges at the end of the line. *v* is the velocity of the travelling wave, which is close to the speed of light in overhead lines. L is the total length of the line.
Type D Method is the used method, other methods are used in special instances.

2.2.2. Type A (single ended) method

The Type A Method estimates fault distance by analyzing single-ended recordings of the travelling wave transient caused by the fault. The algorithm determines the distance using the measured time difference, Δt, between the incident surge and the reflected surge originating at the fault location, which corresponds to the wave's transit time for a complete journey to and from the fault.

$$X_L = \frac{\Delta t \cdot v}{2} \tag{2.3}$$

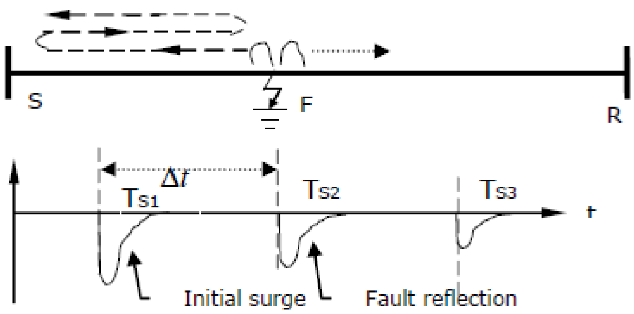

Fig. 2.2. Principle of Type A method

2.2.3. Type E method

The Type E Method uses the switching transients created when a circuit breaker recloses onto a faulted power line. The methods enable determination of the fault distance with high accuracy by measuring the time separation between the incident transient pulse and its reflection from the fault-a short circuit or conductor break.

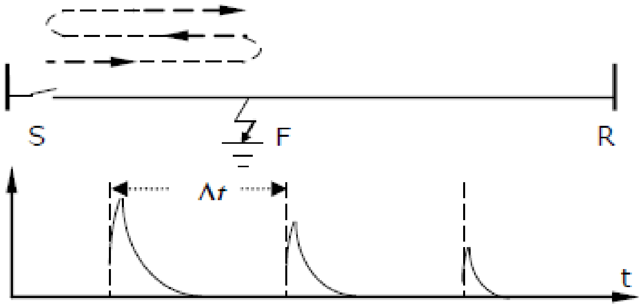

Fig. 2.3. Principle of Type E method

2.2.4. Type W (wide area) method

W-type methods are based on a network-level principle of a comparison of the arrival times of travelling waves at substations. It also acts as an emergency backup when the local fault recorders, the TDU-100E, fail on the line on which the fault has occurred.

The principle involves a multi-step process:

- Reference Point: The first substation that detects the travelling wave surge is called the reference substation.
- Subsequent Stations: All other substations which have detected the surge at the same or later instant than the reference substation.
- Initial Estimation - With each of these subsequent substations, an initial estimate of the fault distance using a Type D Method approach can be determined by comparing the time of arrival of the surge at that substation with the time recorded at the reference station using the shortest electrical path between stations.
- Simulation & Verification: The travel time for a surge from this calculated fault location is then simulated digitally for all the detecting substations.
- Final Location: Although the final location step was not completed in the original text, based on the context, a conclusion is that the location whose simulated time pattern more closely matches the actual recorded time-tag pattern is confirmed as the fault location.

2.3. Comparison with Traditional Fault Location Techniques

Impedance techniques are utilized heavily in conventional line protection of transmission lines. They are either single-ended or double-ended depending on measurements being taken from one side or both sides of the line, respectively. Although the techniques are not very complex and do not require rapid data acquisition, they are very sensitive to fault and system parameters [11].

One of the biggest hurdles to the application of impedance-based methods is that they are sensitive to system models' accuracy and line parameters' accuracy. Fault resistance, particularly large fault resistance, causes large errors during distance measurement [12]. Additionally, in tapped loads or multi-terminal lines, impedance-based methods may provide equivocal responses.

Traveling wave approaches have several important benefits in this use. Since they are based on the physical wavefront time of propagation, they are extremely fault resistance and line loading insensitive. Their dependability is largely a matter of satisfactory time synchronization and high-frequency data capture, both of which are more feasible with current technology. This table directly shows the difference between this methods [13]:

Table 2. The difference between these methods:

Criteria	Impedance-Based Method	Traveling Wave Method	Advantage
Accuracy	Moderate	High	Traveling Wave
Speed	100+ ms	<10 ms	Traveling Wave
Cost	Lower	Higher	Impedance-Based
Sensitivity to Fault Resistance	High	Low	Traveling Wave
Implementation Complexity	Low	High	Impedance-Based

In comparison studies, wave methods have been shown to be more performing in long transmission lines, particularly over 100 km, such as 220 kV overhead transmission lines. Their fault location within a few hundred meters, and even more so, renders them highly suitable for rapid system restoration and minimization of outage times [14].

In addition, while impedance methods require post-fault steady-state measurements, wave propagating methods can utilize the first few milliseconds of the fault, significantly reducing protection system response time. Such rapid detection is important for transient stability in multimachine systems [15].

2.4. Practical Application and Signal Processing

Installation of a propagating wave fault location system involves integrating advanced hardware and software. The key components include [16]:

- High-Speed Measurement Instruments (HSMUs): These should be able to sample voltage and current at a speed greater than 1 MHz, as needed in capturing high-frequency wavefronts.

- GPS Time Synchronization: So that the fault location is calculated accurately, especially in double-ended methods, data from both terminals should be time-synchronized with sub-microsecond precision.

- Digital Recorders and Relays: These should be capable of handling the high-speed data in near real time or in real time.

One of the most significant steps towards implementation is that of applying signal processing techniques. Filtered and processed raw waveform data is needed in order to accurately identify first wavefronts. Standard techniques are [17]:

- Wavelet Transform: Excels at identifying transient characteristics in non-stationary signals and therefore appropriate to the detection of propagation wave fronts..

- Short-Time Fourier Transform (STFT): Very appropriate for frequency-domain analysis over short time periods, but less precise in time localization compared to wavelets.

- Cross-Correlation: Particularly handy in double-ended systems in an effort to determine the difference in wave arrival times at both ends.

Numerous utilities worldwide have begun to include propagating wave technology in their schemes for protection. Excellent examples are in China, India, and Europe, where long EHV transmission lines are rendering traditional approaches less reliable. These systems have shown excellent performance under real fault conditions [18].

In addition, advancements in hardware like photonic sensors and next-generation digital signal processors further improve the applicability of wave propagation techniques. Combining wide-area monitoring systems (WAMS) with phasor monitoring units (PMUs) also facilitates more comprehensive and coordinated protection measures [19].

2.5. Challenges, Accuracy Factors, and Future Trends

Nevertheless, wave fault location by propagation has several drawbacks. The primary issue is the high requirement of speed and accuracy in the data collection process that raises the cost and complexity of the system. Noise in the signal—due to external interference or switching transients—can give rise to incorrect identification of the wavefront [20].

Another challenge arises from line discontinuities as splices, transformers, and tap points, which may generate reflections and complicate waveform interpretation. This calls for the use of accurate line models together with sophisticated filtering techniques to segregate true fault signals from the artifacts [21].

Besides, accuracy is also compromised by:

Fault Inception Angle: This controls the initial waveform shape and energy.

- Line Length and Configuration: More complex geometries and longer lines introduce additional attenuation and dispersion.

Bandwidth of Sensors: Narrow bandwidth can restrict frequency components detected, hence affecting detection fidelity.

In an attempt to surmount these challenges, more recent studies have tried to use machine learning and AI for the interpretation of propagating wave data [22].

Additionally, integration with smart grid technologies makes it worth mentioning that the spreading wave systems are beneficial for assisting self-healing grid initiatives. Their very quick response may be used for triggering automatic reclosers, disconnecting faulty sections, and transferring power in milliseconds [23]. While traveling wave systems are highly accurate, they are quite expensive and involve sophisticated instrumentation.

Synchronization errors and wave reflections lead to noise and decreased precision. To meet these challenges, artificial intelligence and machine learning are increasingly employed to improve waveform analysis and diminish interpretation errors [24]:

Table 3. Analysis and diminish interpretation errors

Factor	Impact on Accuracy
Synchronization Error	Leads to major location errors
Line Parameter Mismatch	Causes estimation deviation
Reflections at Taps	Complicates waveform analysis
Sensor Bandwidth	Limits transient detection range

Future directions include the creation of low-cost, small propagating wave monitoring devices and applications of fiber-optic cables for simultaneous communication and wave sensing. There is also interest in combining wave-based methods with impedance techniques into hybrid fault location systems to gain the best of both worlds [25].

CHAPTER THREE:
RESEARCH APPROACH AND METHODOLOGY

3.1. Nature of traveling waves

This technique is based on the idea of propagating waves. This proposal is based on the fact that any disturbance on a transmission line generates travelling waves that travel along the transmission line. These waves are the consequence of charging and discharging the line capacitance and line inductance of the transmission line. Every wave, with a frequency ranging from a few kilohertz to several megahertz, moves at a speed that is nearly as great as that of light. Time-of-arrival measurements of surges induced by the fault at the terminals are required for fault location of Fault on Transmission Line using calculations utilizing travelling wave-based methodologies. You may track the wave's progress by keeping an eye on the transient voltage and current signal on a single bus. Current and voltage transformers that are already in use can be used to test the current and voltage of AC transmission lines. On the travelling wave concept, this technique relies. Upon the observation that any disturbance on the transmission line causes travelling waves to propagate down the transmission line, this concept has been put forward. The line inductance and line capacitance of the transmission line get charged and discharged, causing these moving waves. The propagation speed of each wave, which ranges from a few kilohertz to several megahertz, is close to the speed of light. For the calculation of fault distance via travelling wave-based procedures, the measurements of the time when the surges caused by the fault are visible at the terminals must be taken. Transient voltage signal and transient current on a single bus can be used to see the traveling wave. Traditional current and voltage transformers provide simple and cost-effective measurements in AC transmission lines.

3.2. Basic Principles of Traveling Waves

A fault on a line, which occurs at any time except at the zero crossing of the voltage, generates a traveling wave, which propagates from the fault location to both ends of the line with speed close to the speed of light. The same principle is illustrated in Figure 1 for an elementary transmission line in case of a fault on the line.

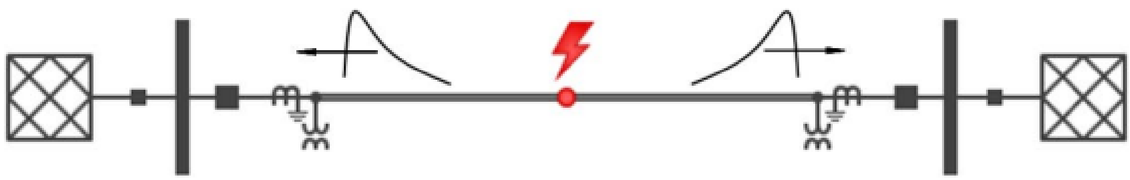

Fig. 3.1. Simple principle of traveling wave propagation

Traveling waves can be deduced as result from the solution of the linear differential equation system for transmission lines (telegraph equations). For a lossless transmission line the following pair of coupled first order partial differential equations describe voltages $v(x,t)$and currents $i(x,t)$ on the line:

$$\frac{\partial v(x,t)}{\partial x} = -L^{'} \frac{\partial i(x,t)}{\partial t} \tag{3.1}$$

$$\frac{\partial i(x,t)}{\partial x} = -C^{'} \frac{\partial v(x,t)}{\partial t} \tag{3.2}$$

Whereas L' is the inductance of the line in per unit and C' is the capacitance in per unit. This can be combined into the wave equations (equation of d'Alembert) as follows:

$$\frac{\partial^2 v(x,t)}{\partial t^2} = L^{'}C^{'} \frac{\partial^2 v(x,t)}{\partial x^2} \tag{3.3}$$

$$\frac{\partial^2 i(x,t)}{\partial t^2} = L^{'}C^{'} \frac{\partial^2 i(x,t)}{\partial x^2} \tag{3.4}$$

The general solution of the wave equations can be expressed as a sum (superposition) of a traveling wave f in forward and g in backward direction:

$$v(x,t) \ = f(x-ct) \ + g(x+ct) \tag{3.5}$$

$$i(x,t) \ = \frac{1}{Z_W}(f(x-ut) \text{ -} g(x+ut)) \tag{3.6}$$

Whereas $c = \frac{1}{\sqrt{L^{'}C^{'}}}$ is the propagation speed and $Z_W = \sqrt{\frac{L^{'}}{C^{'}}}$ is the characteristic impedance of the line. For the case of a lossy transmission line, the equations have to consider resistance and conductance losses too. A more detailed discussion can be found in [1] and [2] or any advanced text book on electrical engineering.

At the line terminals the traveling waves, which result from a sudden change of voltage and current, can be detected as high frequency pulses. Protection devices or fault locators use specific algorithms to time stamp the arrival times of the traveling waves. From time delays of arrival times measured the location of a fault can be calculated easily and with high accuracy (of up to 300m, which is about one tower span). Due to dispersion effects the shape of the waves is slightly stretched when traveling along the media of a power line. This must be kept in mind by the protection relays at time stamping the arrival of the waves. Whenever traveling waves hit a terminal of a line (or the location of a fault), part of the wave is transmitted, a part is reflected and some is absorbed. Upon reflection, the polarity of the traveling wave pulse is inverted, as shown in Figure 3.2. With current traveling waves the direction of the pulse is determined by the polarity in which the wave passes via the current transformer (CT) as well.

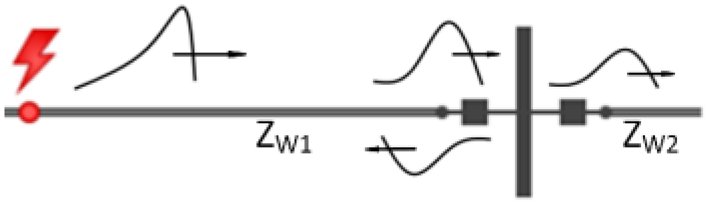

Fig. 3.2. Traveling waves divide into transmitted and reflected waves at discontinuities

Propagation of traveling waves including their reflections are commonly visualized using Bewley lattice diagrams, as shown in Figure 3.3. The gradient of the propagation lines is proportional to the propagation velocity of the lines. For different media, i.e. in cable and overhead line mixed topologies, even different velocities can be shown in the same graph.

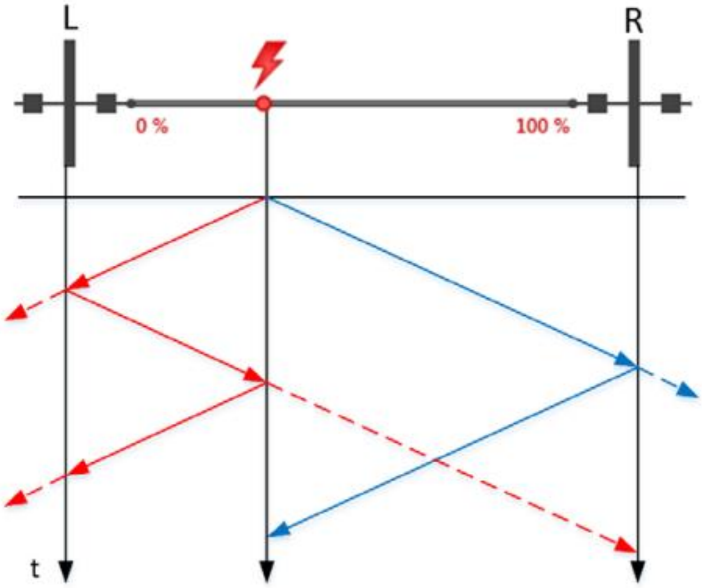

Fig. 3.3. Bewley lattice diagram showing the propagation of traveling waves over time

As the topology of the power system becomes more complicated, e.g. with multiple buses, parallel lines, and neighboring lines, algorithms in the equipments should differentiate the reflected traveling waves from disparate points with topology discontinuities. Occasionally this is quite problematic and in fact making decisions like that is not very easy to do reliably, as even minor circuitry specifics could produce reflections too, so that certain robust algorithms simply employ the very first traveling wave front detected. For example in the following case, shown in Figure 3.4, it is not easy to distinguish a traveling wave, reflected from the fault location on the protected line back to the local end, from a reflection from a predecessor line in backward direction or from a reflection from the remote end of the line.

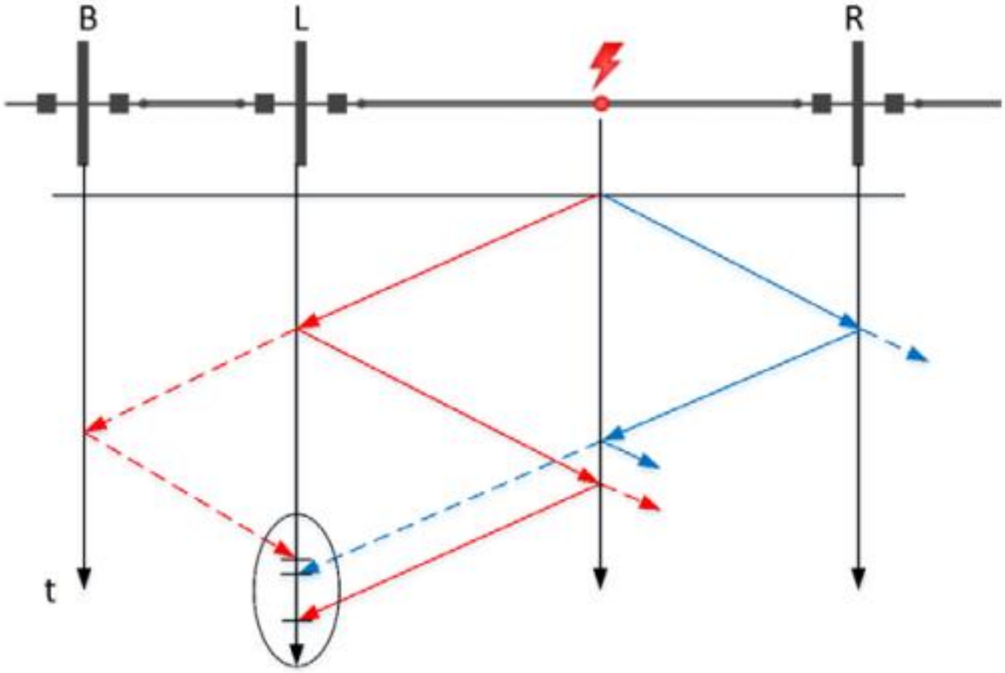

Fig. 3.4. Challenges for discrimination of traveling wave reflections

For secondary equipment the detection of traveling waves is possible on the secondary terminals of current transformers (CTs) and voltage transformers (VTs). Common CTs have a sufficiently high bandwidth to allow for reliable detection of traveling wave pulses on the secondary current inputs of the devices. For VTs and particularly for CVTs and CCVTs traveling wave surges in the secondary are far more difficult to identify, so that certain rules of traveling wave components rely solely upon current traveling waves (with CVTs and CCVTs only parasitic capacitances offer a path for the high frequencies). But in the future new voltage and current sensors could be possible, which offer better dynamic transfer behaviour for high frequency signals. Protection and fault location elements based on traveling waves have some advantages over phasor-based elements. Since the calculation of the fault location is based on the measurement of time differences between the arrival times of different traveling wave pulses, a high precision for the fault location is possible. Nowadays precise time measurements within digital substation equipment is possible easily, even among different distributed devices, which can be time-synchronized using a common global time reference. The propagation of traveling waves is not affected by series compensation of long transmission lines, wherever they are installed (for impedance based elements series compensations is a big challenge). And traveling waves do not occur in AC transmission lines only. The principle can be applied for HVDC grids too, where an impedance based fault location is not possible at all. Since traveling waves propagate close to the speed of light, the information about a fault is received at the line ends as fast as physically possible and can be processed immediately. For phasor elements based on a data window of one cycle of power system frequency is necessary in order to have correct phasor values. So for future protection relays tripping based on information from traveling waves is possible and allows for tripping times as fast as a few milliseconds only.

3.3. Using Traveling Waves for Fault Location

What is well established and deployed in multiple devices in the field for years already is the application of traveling waves for precise fault location on transmission lines. Both as dedicated fault location devices and as an integrated function within protection relays a more accurate estimation of the location of a fault is possible compared to impedance based principles. All the apparent impedance-based fault location algorithms looking into the line have a limited accuracy due to voltage and current phasor measurement errors and are influenced by numerous factors, which are difficult to compensate for, such as fault impedance (arc resistance), infeed conditions at both the local and remote ends of the line, super-imposed load flow, grounding conditions and mutual coupling with a parallel line. They also depend on correct settings of both positive and zero sequence line impedances, which must be either calculated with precision or determined with an initial measurement of line impedance.

3.4. Parameters that travelling waves depend on

The gradual rise in line voltage may be attributed to a voltage wave traveling from supply source end to the remote end, and the resulting current wave will be attributed to progressive charging of line capacitances. Assume that a current I and a voltage V are established over a length x of the line in a relatively short time t. The back emf created by the magnetic flux produced by the current in this length of the line balances the emf V. The inductance of the length δx is $L\delta x$ (L is line inductance per unit length), hence the flux built up is $IL\delta x$ and the back emf is the rate of building viz. $IL\,\delta x/\delta t$.

So we have

$$V = IL\frac{\delta x}{\delta t} = ILv \tag{3.7}$$

where v represents the wave's propagation speed.

The current I carries a charge $I\delta t$ in time δt, and this charge remains on the line to charge it up to the potential of V. Since the capacitance of length δx of the line is $C\delta x$ (C is the capacitance of the line per unit length), its charge is $VC\delta x$, so we have

$$I\delta t = VC\delta x \tag{3.8}$$

Or

$$I = VC\frac{\delta x}{\delta t} = VCv \tag{3.9}$$

The switching of an emf V on to the line results therefore in a wave of current I and velocity v are given by equations (3.7) and (3.9). Dividing (3.7) by (3.9), we have

$$\frac{V}{I} = \frac{ILv}{VCv} = \frac{I}{V} \cdot \frac{L}{C} \tag{3.10}$$

Or

$$\frac{V^2}{I^2} = \frac{L}{C} \tag{3.11}$$

Or

$$\frac{V}{I} = \sqrt{\frac{L}{C}} = Z_n \tag{3.12}$$

The expression is a ratio of voltage V and current I which has the dimensions of impedance and is therefore here designated as surge impedance of the line. It is also called natural impedance because this impedance has nothing to do with the load impedance, but depends only on the line constants.

From (5) surge impedance Zn which is the ratio of voltage and current having the dimension of impedance is thus:

$$Z_n = \frac{V^2}{I^2} = \frac{L}{C} \tag{3.13}$$

Inductance

$$L = \frac{V^2 C}{I^2} \tag{3.14}$$

Capacitance

$$C = \frac{I^2 L}{V^2} \tag{3.15}$$

3.5. Propagation velocity of travelling wave

To get velocity of travelling wave, multiply (3.7) and (3.9)

$$VI = ILv \times VCv \tag{3.16}$$

$$VI = VILCv* \tag{3.17}$$

Or

$$v^2 = \frac{1}{LC} \tag{3.18}$$

$$v = \sqrt{\frac{1}{LC}} \quad (3.19)$$

Where L is the inductance in H per km and C is the capacitance in F per km for that line..

3.6. Two ended fault location on the transmission line based on travelling wave

The most basic and robust traveling wave based fault location is on two-ended as shown in Figure 5 and has been utilized in certain fault location and protection equipment in the industry (refer to [3] and [4] for more information).

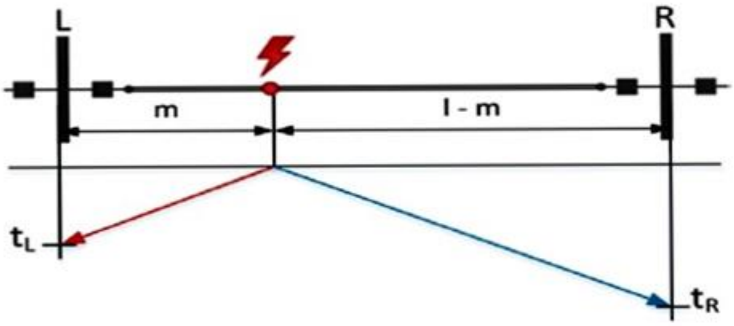

Fig. 3.5. Two-ended fault location using time difference of first arrival times

The arrival times of the traveling waves on both ends of the line are compared and the fault location m is calculated according to the following formula:

$$m = \frac{1}{2}(l + (t_L + t_R)v)$$

Where l is the length of the line, tL and tR are the arrival times of the traveling wave at the local and remote end respectively and v is the propagation velocity. The calculated location solely depends on the precise arrival time stamps of the detected traveling wave fronts and a correct length of the transmission line. Now precise time synchronization of fault locating or protection devices is possible through a Global Positioning System (GPS) based time reference at both ends or synchronization through a network based grandmaster clock, which distributes time via IEEE 1588 Precision Time Protocol (PTP) on an Ethernet network within a substation. For offline fault location, the time stamps at both ends need to be collected in order to calculate. The different arriving times for traveling waves across the various travels can be aligned in a Bewley lattice diagram manually or automatically in a computer program, such that the fault location will be computed and confirmed. The concept can be extended to three-terminal lines or topologies that are multi-ended. For online fault location, as it is implemented within protection relays, the time stamps are transmitted to the remote end immediately mostly using already existing communications channels, which are used e.g. for line differential protection in parallel. Within a protection relay, the traveling wave fault location information may be merged with additional information from an impedance based fault location algorithm, so that a legitimate and accurate statement can be entered into the fault record or forwarded to the control centre.

3.7. Simulink modeling of the traveling wave fault location equation

The SimPower System which is an extension to the Simulink of MATLAB software is used to simulate the power system with two substations. The 165.8 km, 220 kV transmission line as shown in Fig. 6, is represented using distributed parameter model.

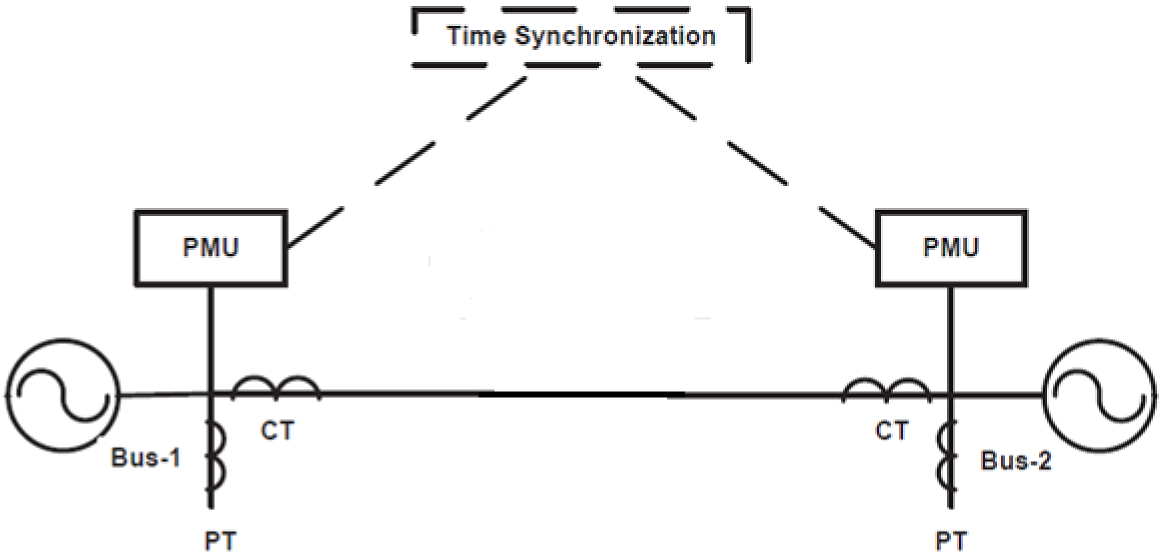

Fig 3.6. Two terminal transmission line

The research is begun by constructing a transmission line block system in Simulink in MATLAB 2023a. The specific blocks used were the following:

1. Three Phase Pi Section Line
2. Three-Phase Series RLC Load
3. Three-Phase Fault
4. Three-Phase V-I Measurement
5. Three-Phase Source
6. Powergui
7. Scope
8. Constant
9. Subsystem (fault locator)

As a result, I have created a Simulink model of overhead line as below (Fig. 7):

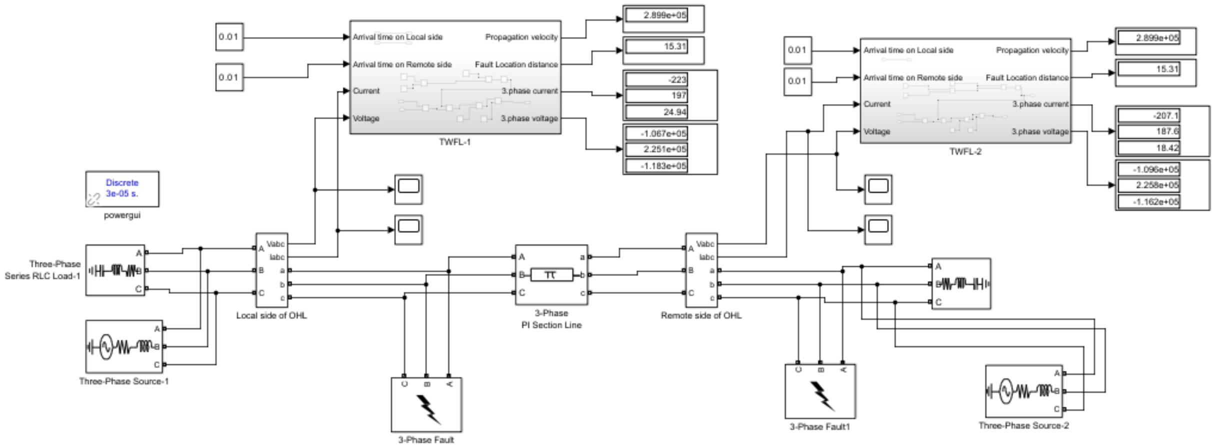

Fig. 3.7. Simulink model of overhead line

The parameters used for each block can be found below.

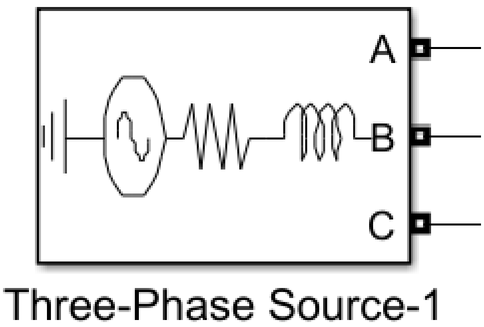

Fig. 3.8. Three-Phase Source system at Local side of OHL

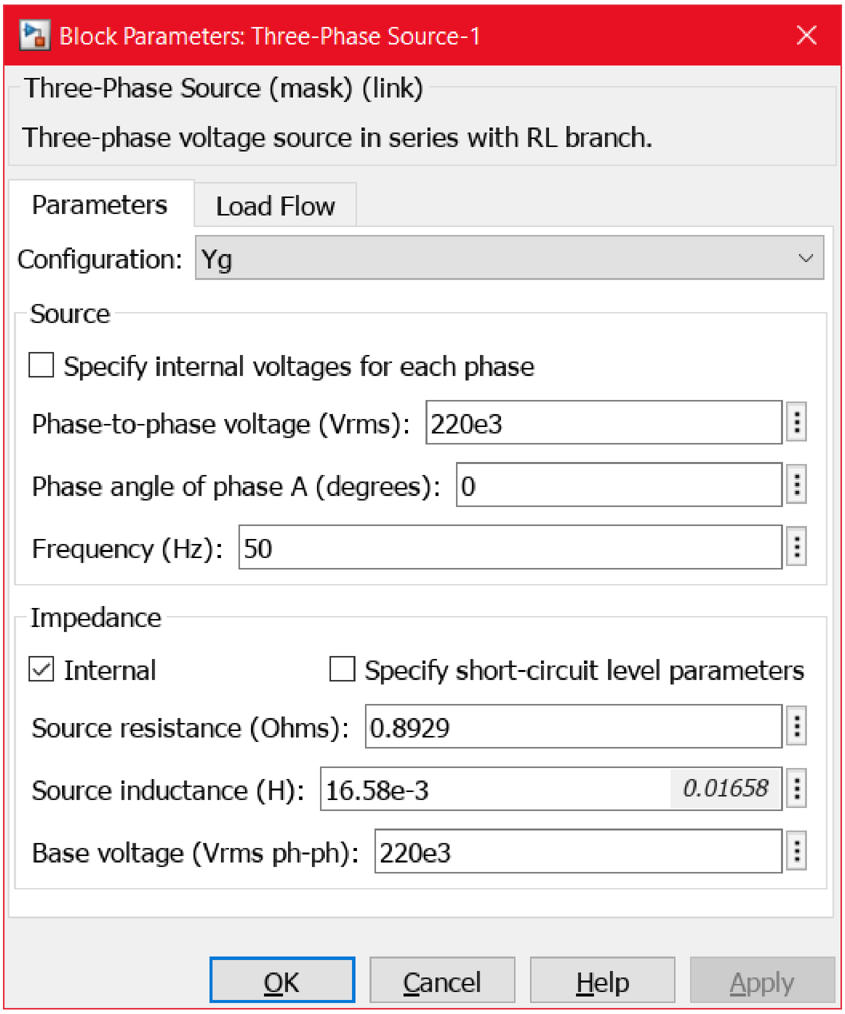

Fig. 3.9. Three-Phase Source block.

The Three-Phase Source block will represent the voltage source of the circuit of the transmission line.

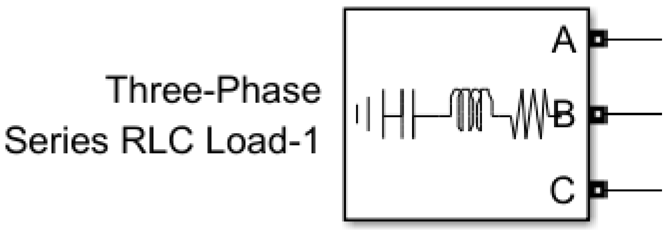

Fig. 3.10. Three-phase load (Local side of OHL - Gala substation)

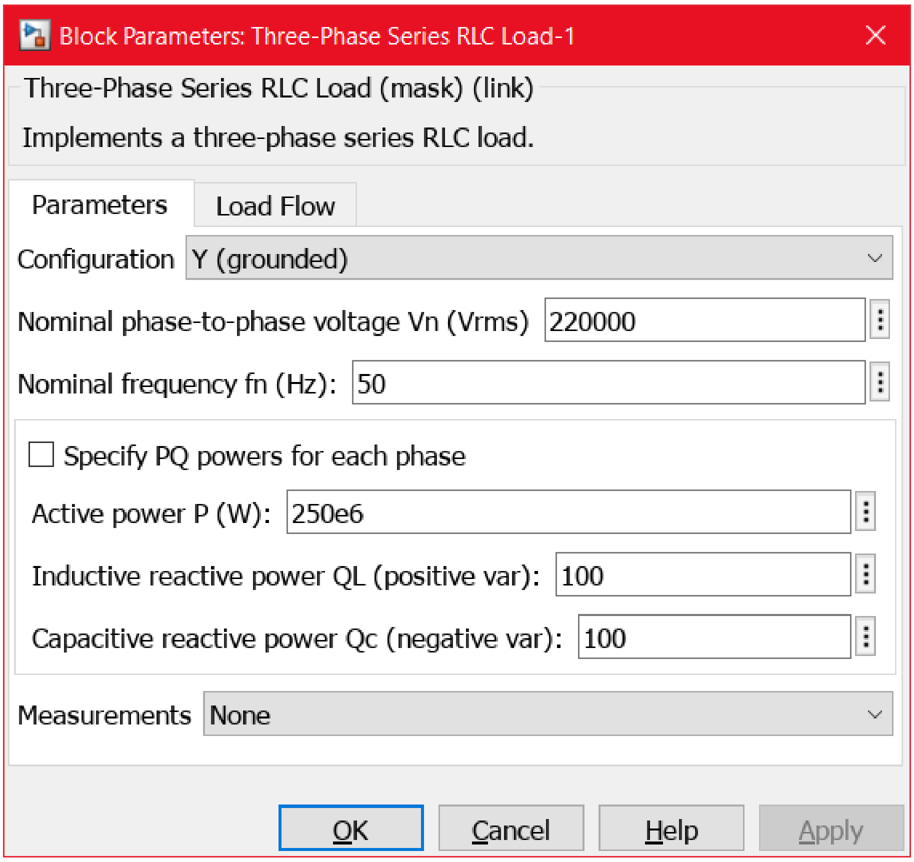

Fig. 3.11. Three-phase load block

Three-Phase Series RLC Load is a series combination of resistance (R), inductance (L), and capacitance (C). It is used for balanced loads where the active and reactive power are proportional to the square of the applied voltage. You can specify the nominal phase-to-phase voltage, frequency, and the active and reactive power for the load. You can also define the connection type (Y-grounded, Y-floating, Y-neutral, or Delta).

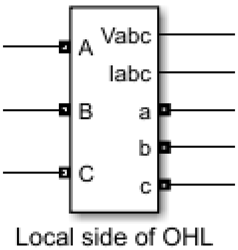

Fig. 3.12. Three Phase V-I measurement.

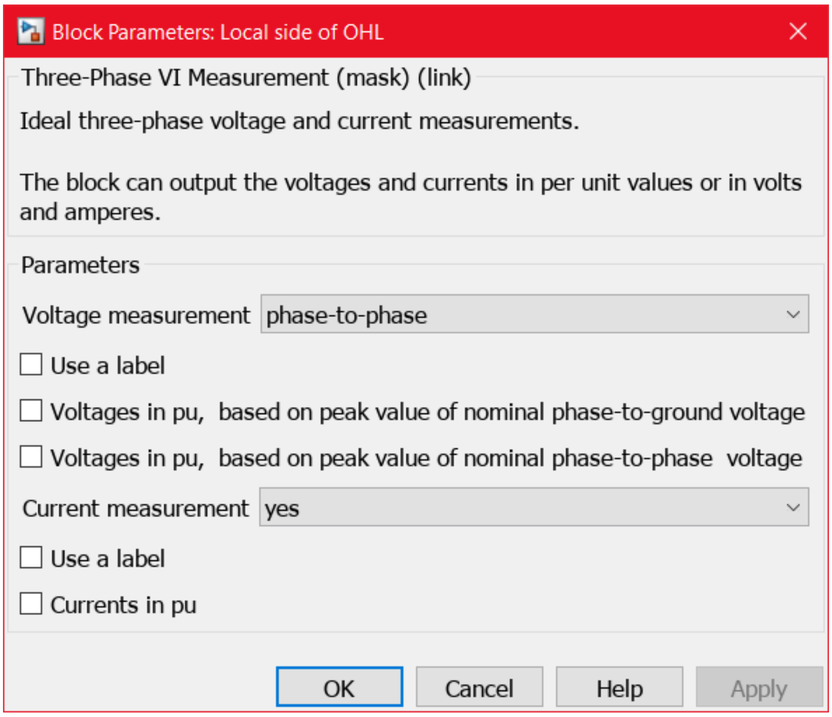

Fig. 3.13. Three Phase V-I measurement block

Voltage (Vabc) and Current (Iabc) values will be sensed on this block.

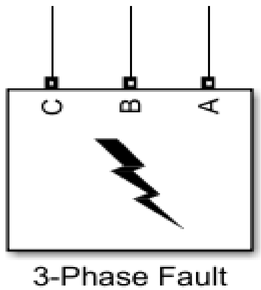

Fig. 3.14. Three-phase fault block.

The Three-Phase Fault block acts as a programmable circuit breaker. It allows you to introduce different types of electrical faults into a three-phase system and observe their effects on parameters like voltage and current.

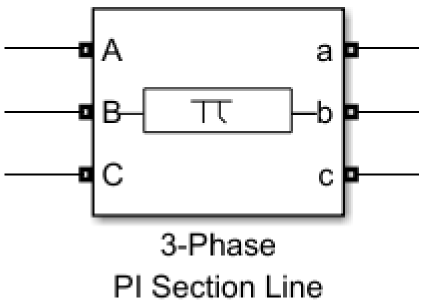

Fig. 3.15. Three-phase PI section line.

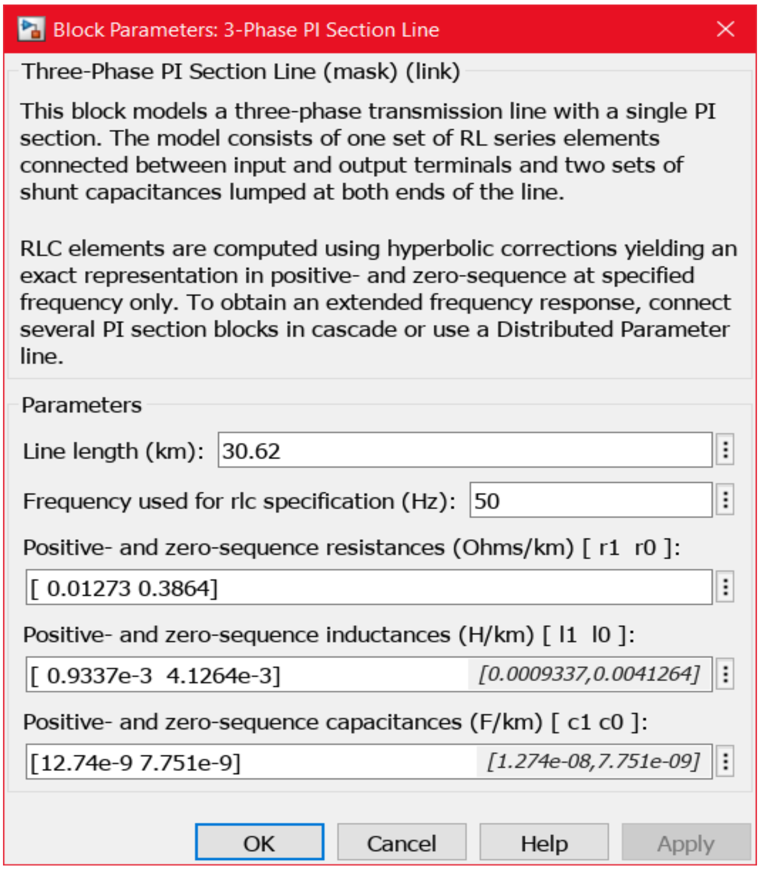

Fig. 3.16. Three-phase PI section line parameters.

The Three-Phase PI Section Line block is a simplified, yet effective, model for simulating transmission lines in power systems, particularly those of medium length. Instead of modeling the resistance (R), inductance (L), and capacitance (C) as continuously distributed parameters along the line, it lumps them into a single PI-shaped equivalent circuit.

This is why you use it:

1. It's an accurate model for medium-length lines
2. It's computationally efficient
3. It's easy to implement
4. It can be adapted for long lines

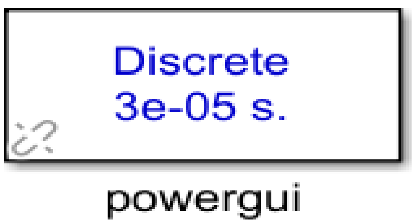

Fig. 3.17. Powergui block

Set the Powergui block to Discrete-time in order to decrease simulation computation time. Set sample time to 3e-5. This is an arbitrary value. Lower values will yield more accurate results at the cost of longer computation time.

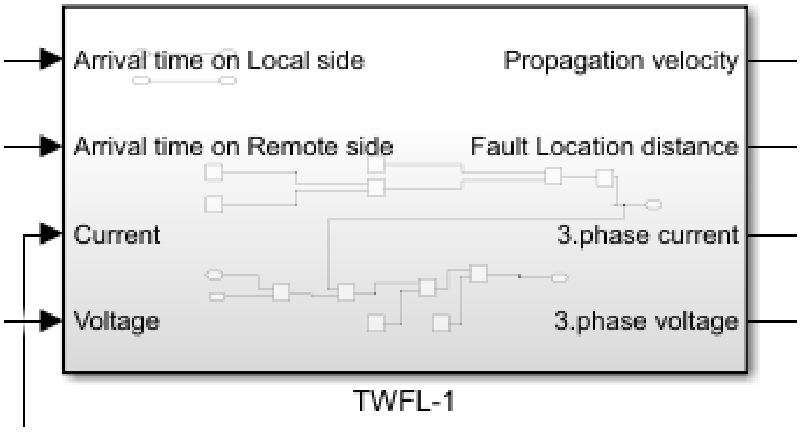

Fig. 3.18. Subsystem of traveling wave fault locator.

A traveling wave fault locator (TWFL) is the device used to define fault distance via traveling waves. It uses sensors at one or both ends of a transmission line to detect the arrival time of the traveling waves generated by a fault. Sophisticated algorithms then use this time-of-arrival data, along with the known length of the line, to calculate the precise fault location.

In TWFL, I have created a subsystem that are included below:

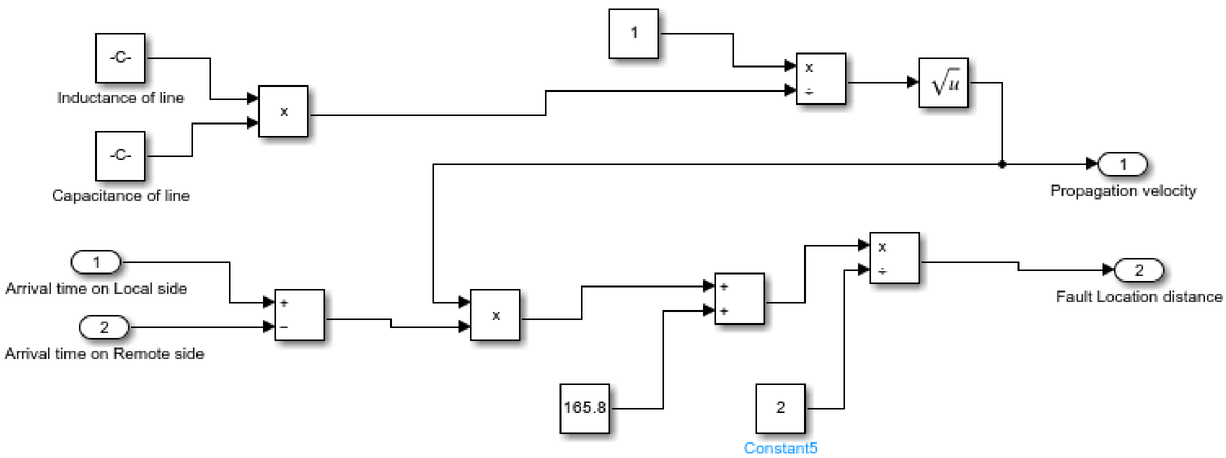

Fig. 3.19. Inside of TWFL

The Simulink model is split into two main sections:

1. Propagation Velocity Calculation

This part of the model calculates the speed at which the fault wave travels down the transmission line. Inputs: It takes the line inductance (L) and line capacitance (C) as inputs. These are the two fundamental electrical properties that determine the propagation velocity. The model uses the formula $v = \sqrt{\frac{1}{LC}}$ to calculate the propagation velocity. This is a well-known equation for calculating the speed of an electromagnetic wave on a transmission line.

2. Fault Location Distance Calculation

This computation is based on the fault wave arrival time difference and propagation speed, which calculates the fault distance from one of the line ends. Arrival time on Local side: Time at which the fault wave arrives at the local substation (measurement point). Time of arrival at Remote side: Time to which the fault wave has arrived at the remote end.

Line length (165.8): Sum of the transmission line length, in the form of a constant. Formula: The model uses the following formula to calculate the fault distance:

Where: l is the length of line, v is propagation velocity, and (tL-tR) is the time difference between the fault wave from remote to local substation.

$$m = \frac{(l+(t_L - t_R)v)}{2}$$

Where: l is the total length of the line, v is the propagation velocity, (t_L-t_R) is the time difference between the fault wave arriving at the remote and local substations.

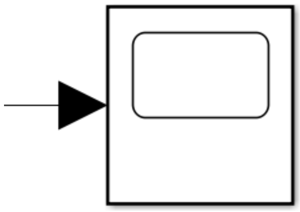

Fig. 3.20. Scope block.

I will use a Scope block inside Simulink to show and inspect signals in your model at the time of simulation.

CHAPTER FOUR:
RESEARCH RESULTS AND ANALYSIS

In this section, results will be presented that were produced by following the methods presented in the study were discussed. When the Time-Frequency model (S-Transform) is simulated in its In its entirety, the following findings emerged as a consequence of the process.

4.1. Pre-fault Results

Figure 24 and Figure 25 shows the pre-fault voltage waveform on local and remote side of the line, obtained by simulating the system with no faults introduced. This result is the state of the system before the occurrence of fault. The sinusoidal pattern in the voltage waveform of all three phases is very close to that of a purely sinusoidal wave when there is no fault. The magnitude in this fault-free system is around 2.2 x 10^5 on the logarithmic scale, showing no change.

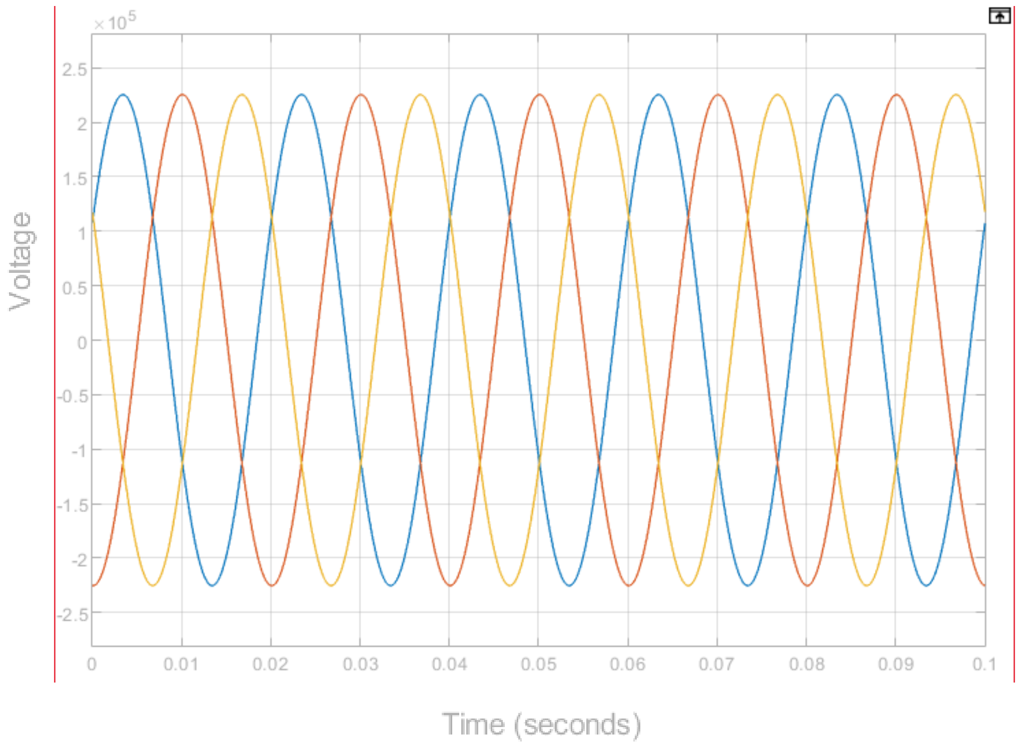

Fig 4.1. Pre-fault voltage on local side of OHL.

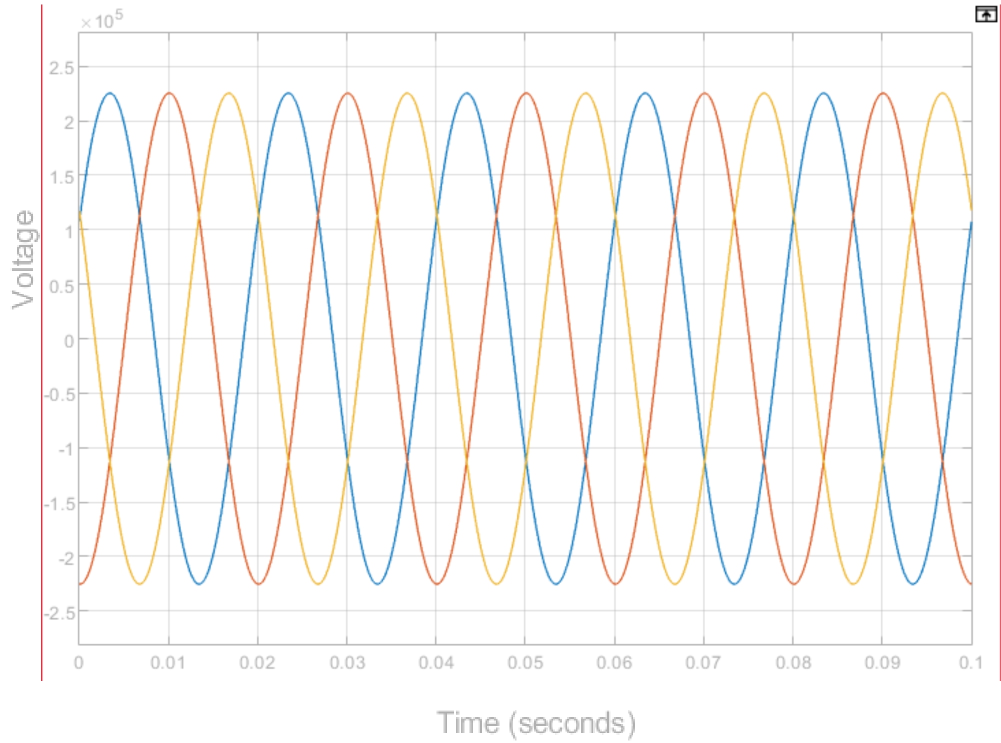

Fig 4.2. Pre-fault voltage on remote side of OHL.

Similarly, Figure 26 and Figure 27 shows the waveform for pre-fault current in the three phases. The magnitudes of the current in the three phases are almost identical; each is about 90 A value, indicating there is no flow of fault current.

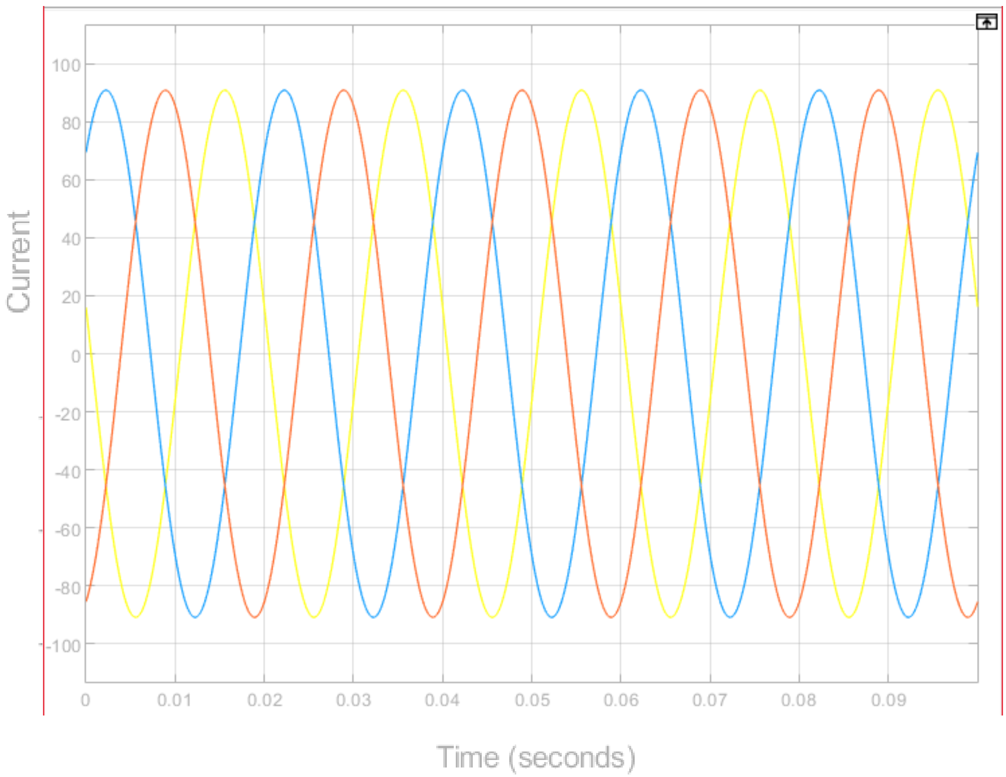

Fig 4.3. Pre-fault current on local side of OHL.

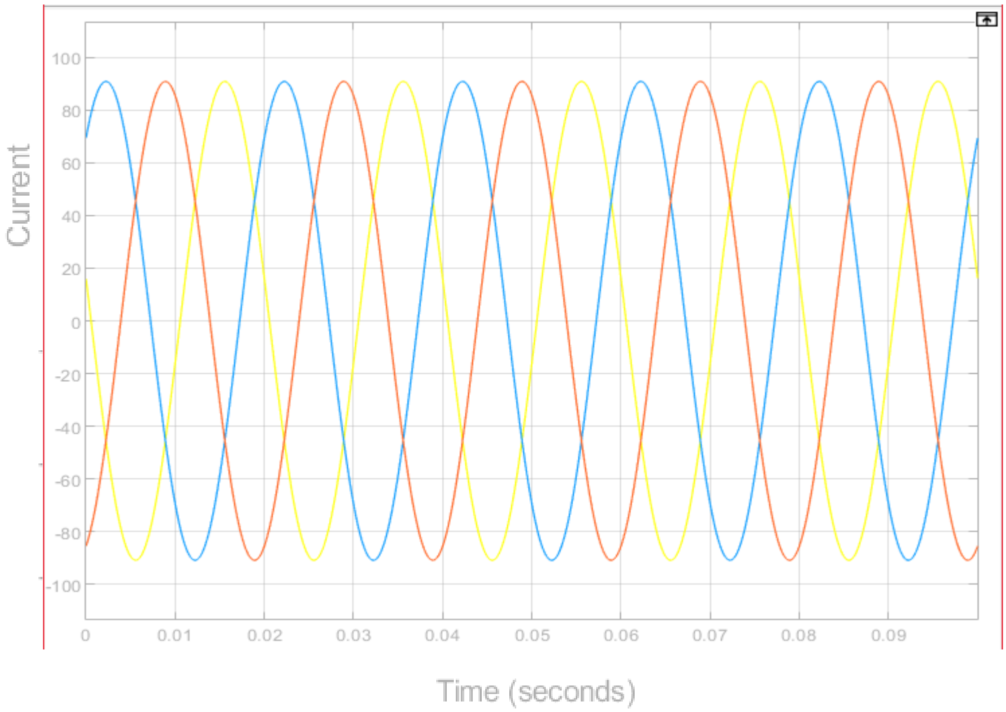

Fig 4.4. Pre-fault current on remote side of OHL.

4.2. Line-to-ground (A-G) fault Results

During the line-to-ground fault on A phase of the line, the voltage in the corresponding phase dropped to zero, while the voltage in the healthy phases decreased slightly, reaching approximately 2 x 10^5 pu at the point of the fault. From the voltage waveform for a three-phase A-G fault shown in Fig. 27 and Fig. 28, the fault was initiated at 100 milliseconds and lasted until it was cleared at 200 milliseconds. The regular sinusoidal pattern of the voltage waveform took an irregular and distorted form when the fault occurred and returned to the sinusoidal waveform pattern once the fault was cleared.

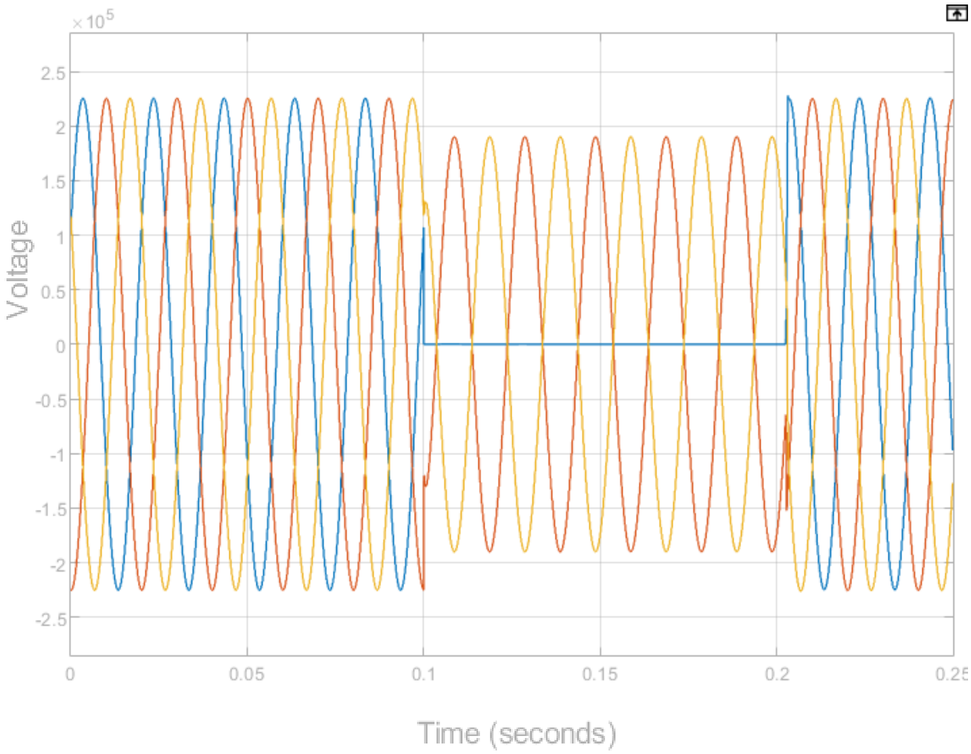

Fig 4.5. A-G fault voltage on local side of OHL.

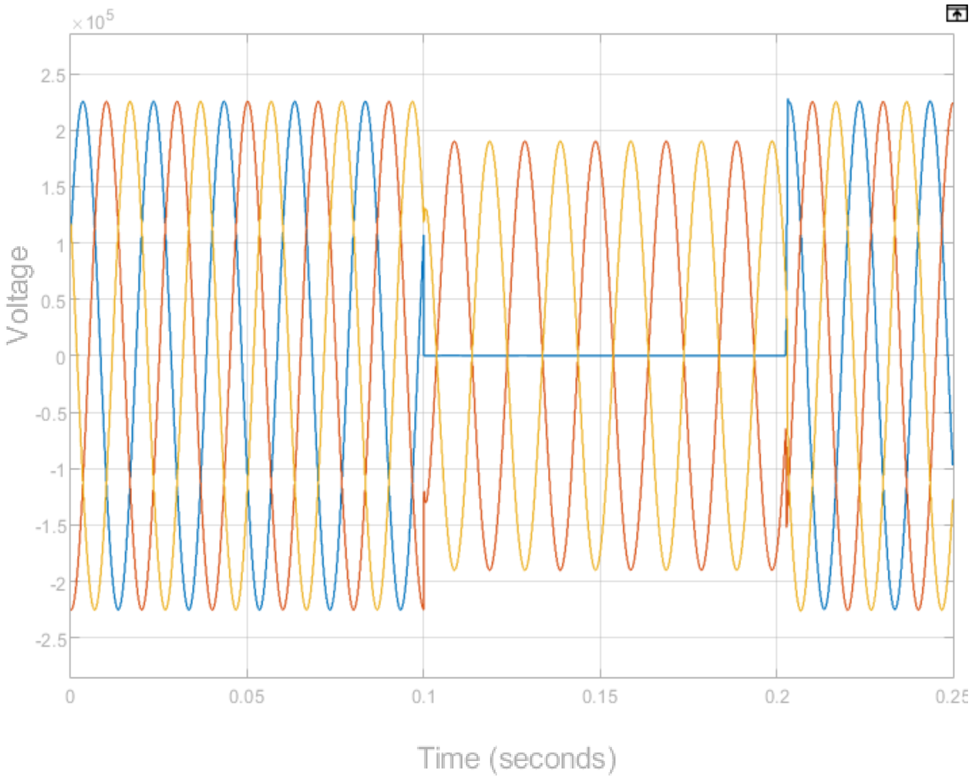

Fig 4.6. A-G fault voltage on remote side of OHL.

During the time of the fault, which lasts approximately 100 milliseconds, there is a spike in the magnitude of current in the faulty phase A. As the voltage drops to zero, the current in the faulty phase increases to about 1500 A, whereas the current in the healthy phases does not change at all. The current amplitude of the faulty phase is uniform with the present magnitude of the healthy phases at the instant the phase A to ground fault is cleared (Fig. 29 and Fig.30).

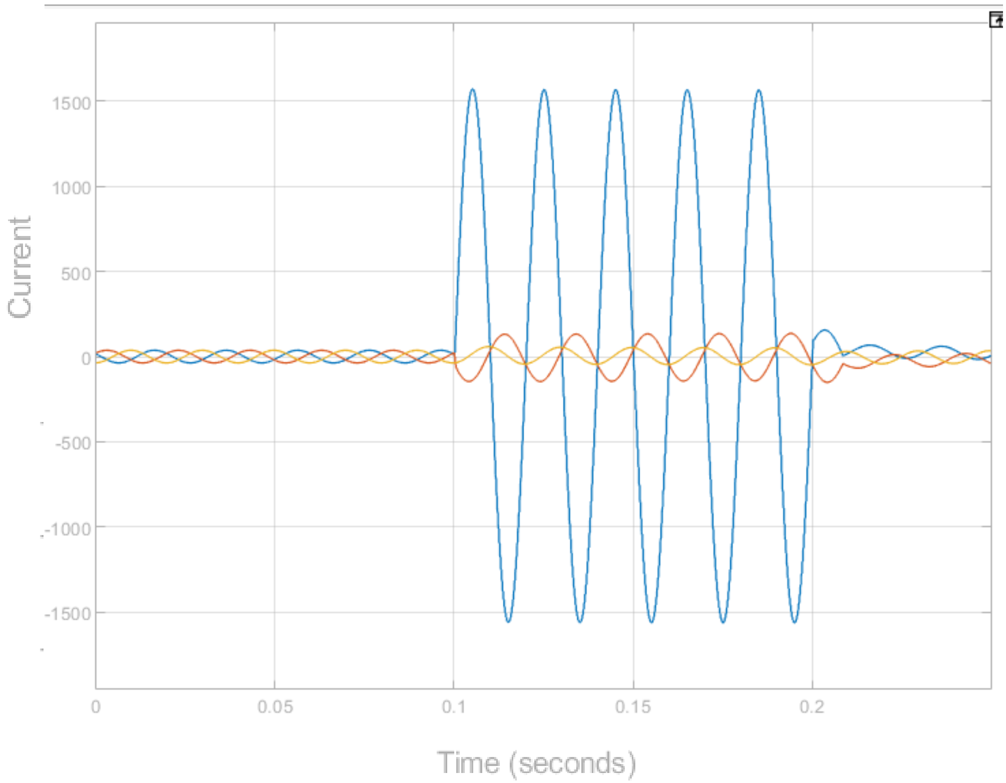

Fig 4.7. A-G fault current on local side of OHL.

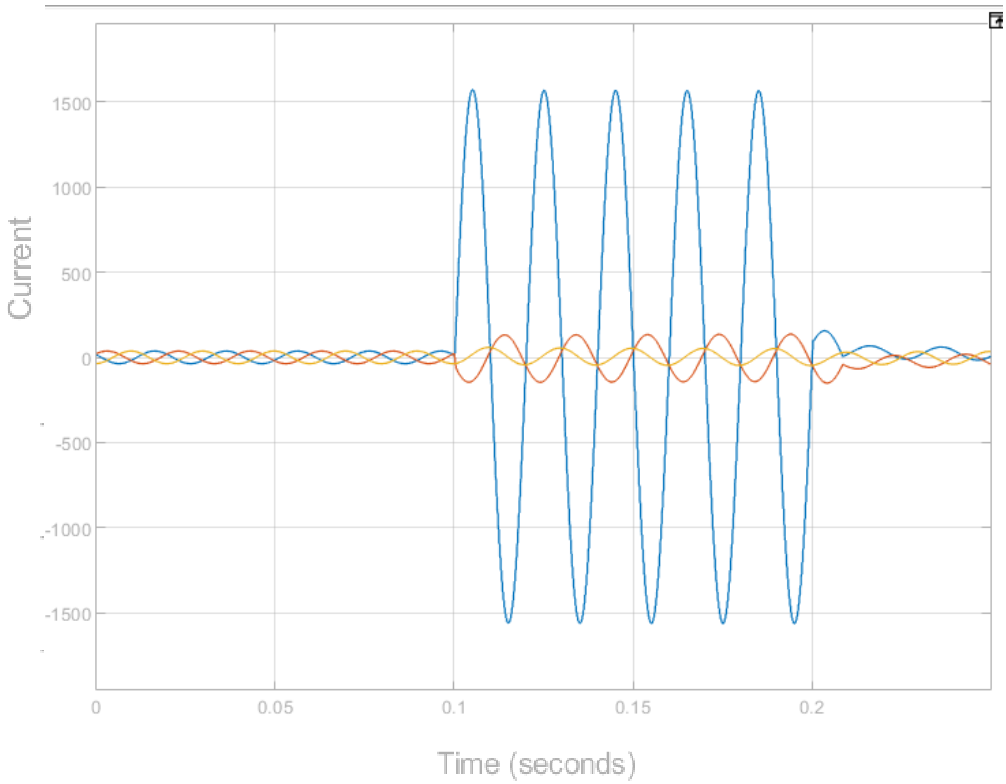

Fig 4.8. A-G fault current on remote side of OHL.

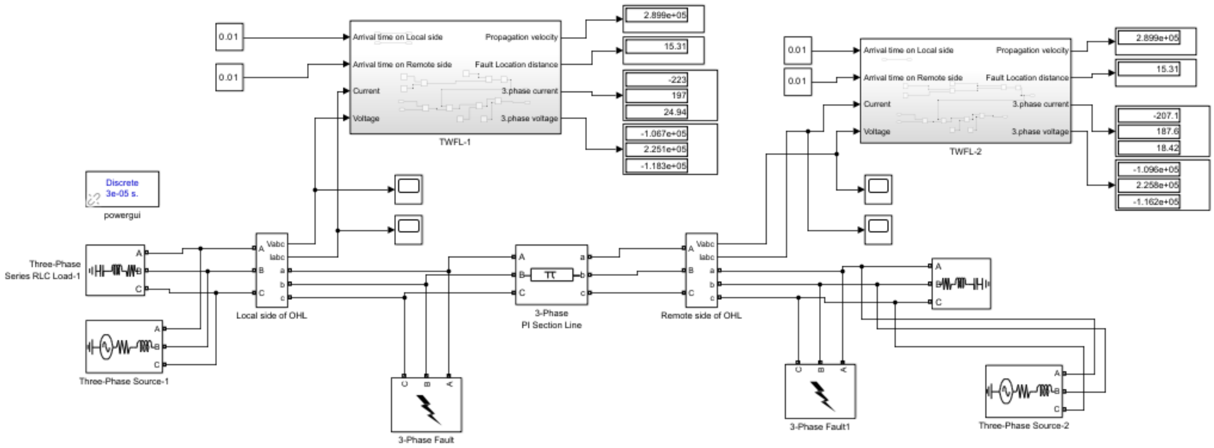

Fig. 4.9. A single line to ground fault on the transmission line was located at 15.61 km using the travelling wave model.

4.3. Double line-to-ground (AB-G) fault results

A double line-to-ground fault was simulated between stages AB and G. The magnitude of the voltage as time varies is shown in Fig. 31. And Fig.32. From these figures, it can be observed that the voltage magnitudes of faulty phases A and B decrease during the fault and follow almost a similar pattern. The fault occurs around 250 milliseconds. During the fault, the voltage magnitude in the healthy phase C spikes to about $1.9x10^5$ pu. Upon the fault clearing at 200 milliseconds, the voltages at phases A and B returned to normal and coincided with the healthy phase.

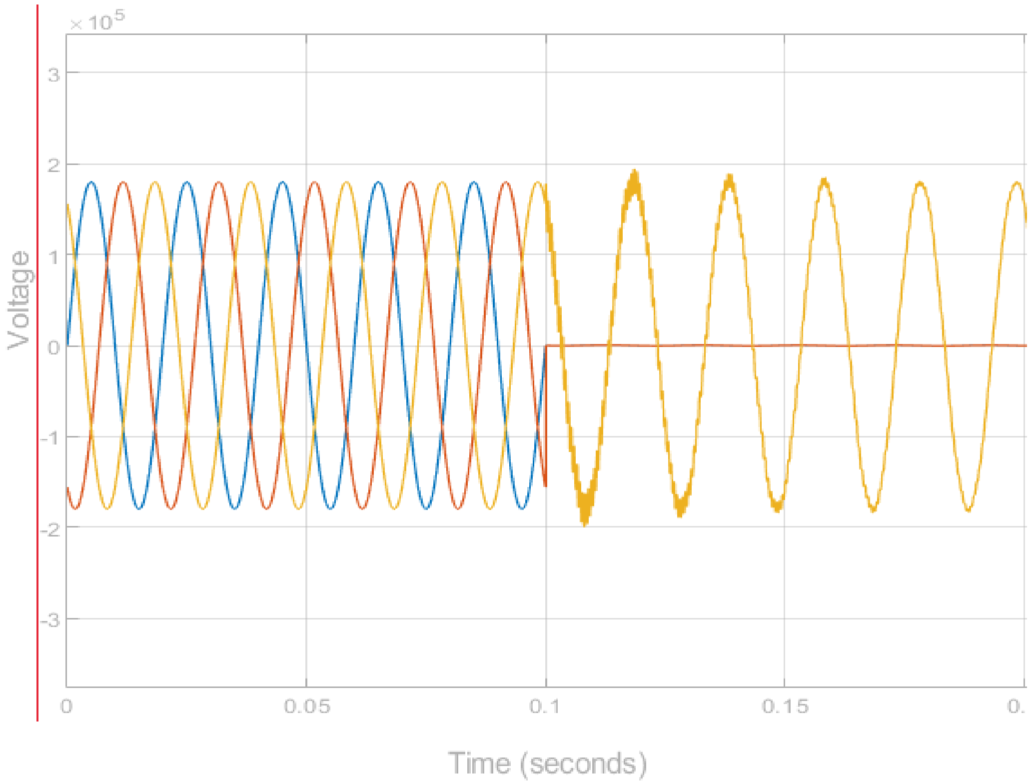

Fig 4.10. AB-G fault voltage on local side of OHL.

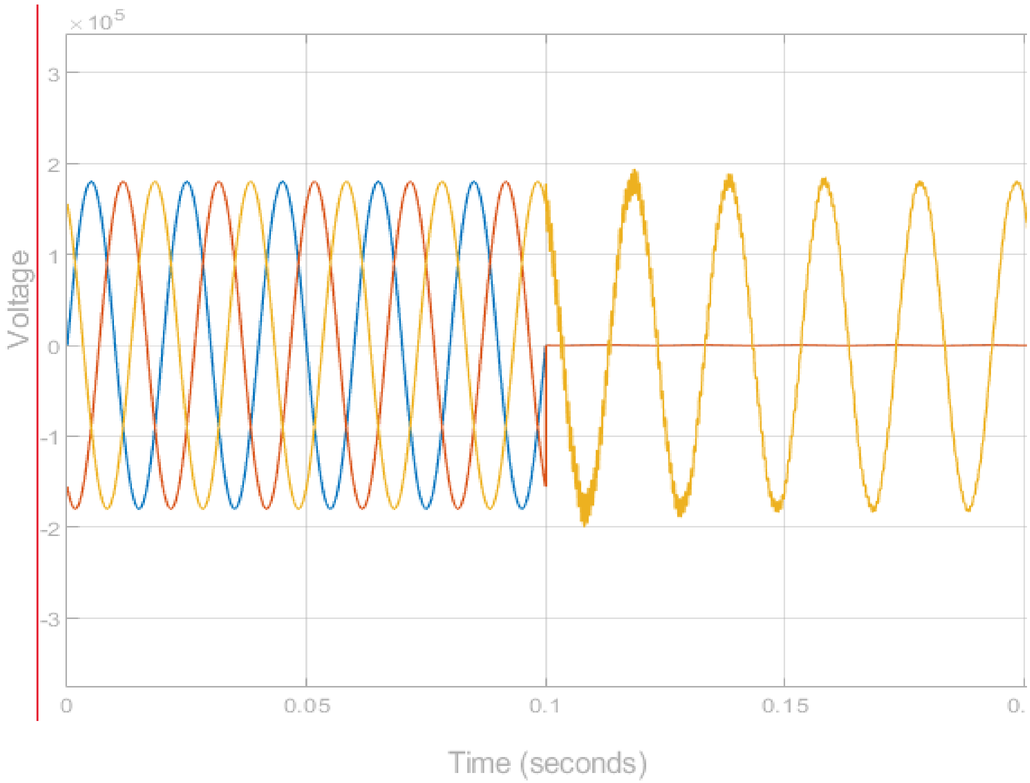

Fig 4.11. AB-G fault voltage on remote side of OHL.

During the occurrence of a double line-to-ground fault, the magnitudes of the current in faulty phases A and B increase, while the current in the healthy phase drops to almost zero around 100 ms. The magnitudes of the faulty phase currents in Fig. 33 and Fig. 34 rise to almost 1500 A. This trend continues until the fault is resolved at about 200 milliseconds.

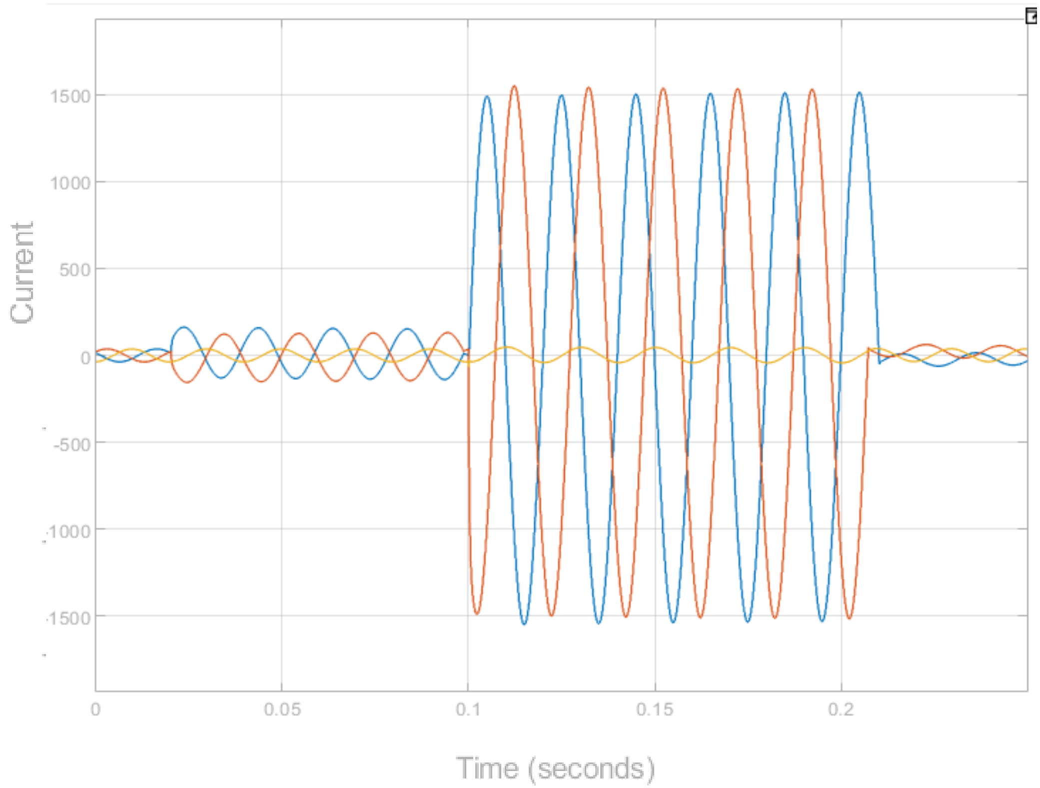

Fig 4.12. AB-G fault current on local side of OHL.

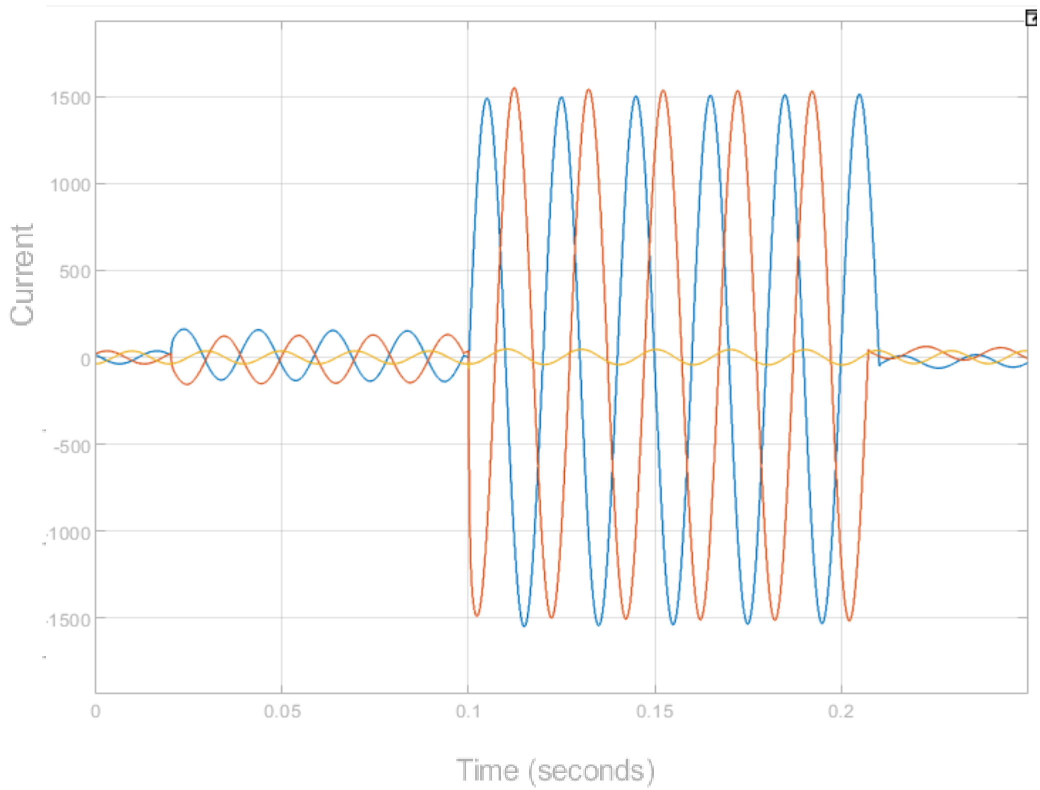

Fig 4.13. AB-G fault current on remote side of OHL.

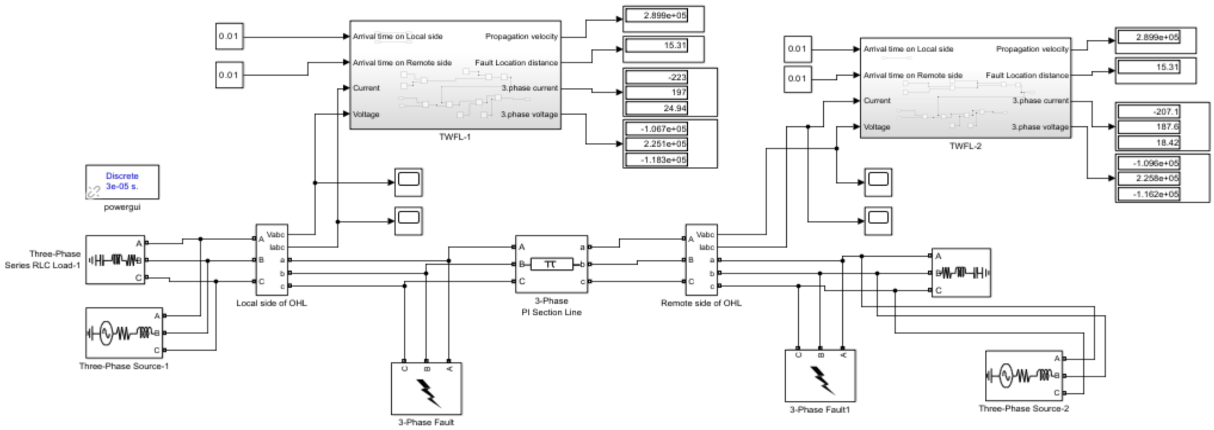

Fig. 4.14. AB-G fault on the transmission line was located at 15.61 km using the travelling wave model.

4.4. Line-to-line (AB) fault results

Fig. 37 and Fig.38 show the simulation result after a three-phase double line fault has been applied at approximately 100 milliseconds. In fact, it was noticed that the voltage magnitude in the two faulty phases A and B reduced to approximately $0.8x10^5$ pu. Throughout the time of the fault, which involved a line-to-line fault at approximately 200 milliseconds, the voltage amplitude on the defective phases consequently fell. Most impressively, the voltage magnitude of the healthy phase C remained unchanged through the experiment at approximately 1.9×10^5 pu. The faulty phases continued to drop until the faults were cleared at 200 milliseconds. Once the faults were resolved, the waveform of the voltage magnitude went back to normal, steady state, with the system fully recovered.

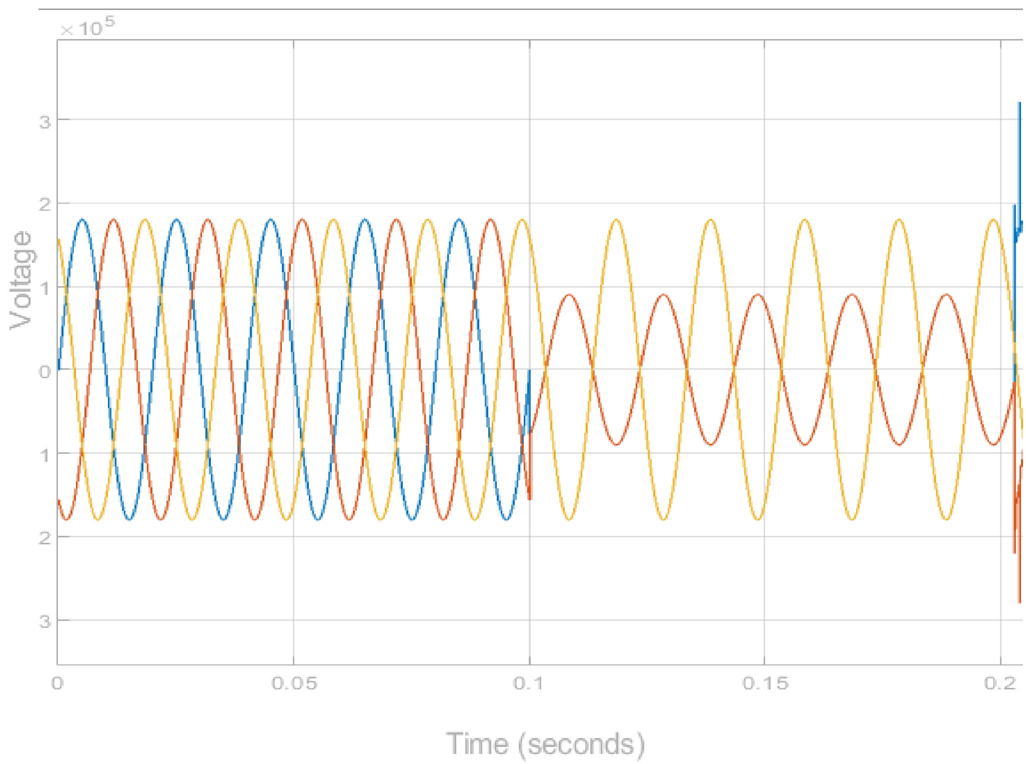

Fig 4.15. AB fault voltage on local side of OHL.

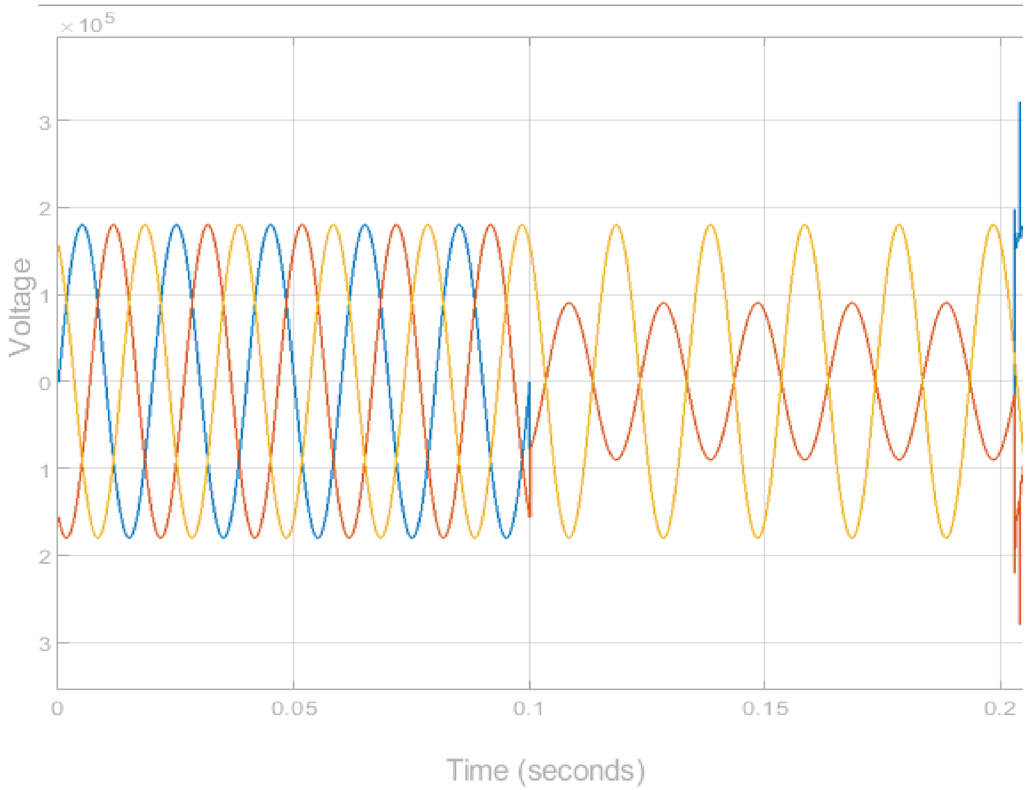

Fig 4.16. AB fault voltage on remote side of OHL.

Fig. 39 and Fig.40 show the result that during the fault, which happened at around 100 milliseconds with a three-phase line-to-line fault between lines A and B, the current magnitude in faulty phases increased to 1500 A, while the current amplitude in the healthy phase C remained unchanged, until the fault between lines A and B was cleared at 200 milliseconds.

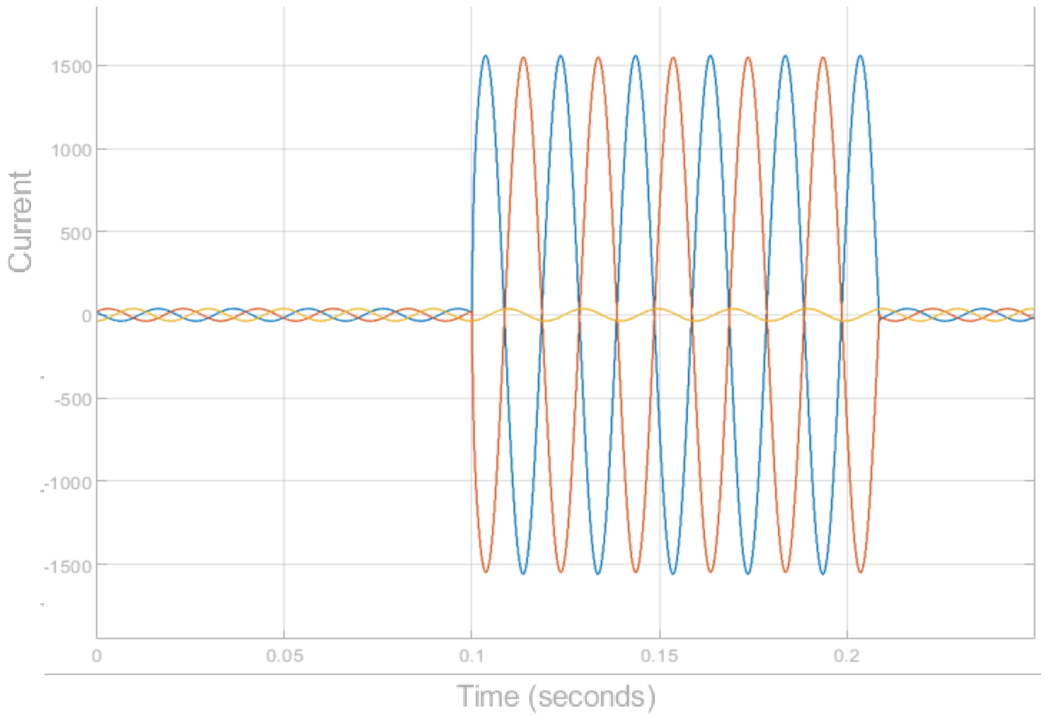

Fig 4.17. AB fault current on local side of OHL.

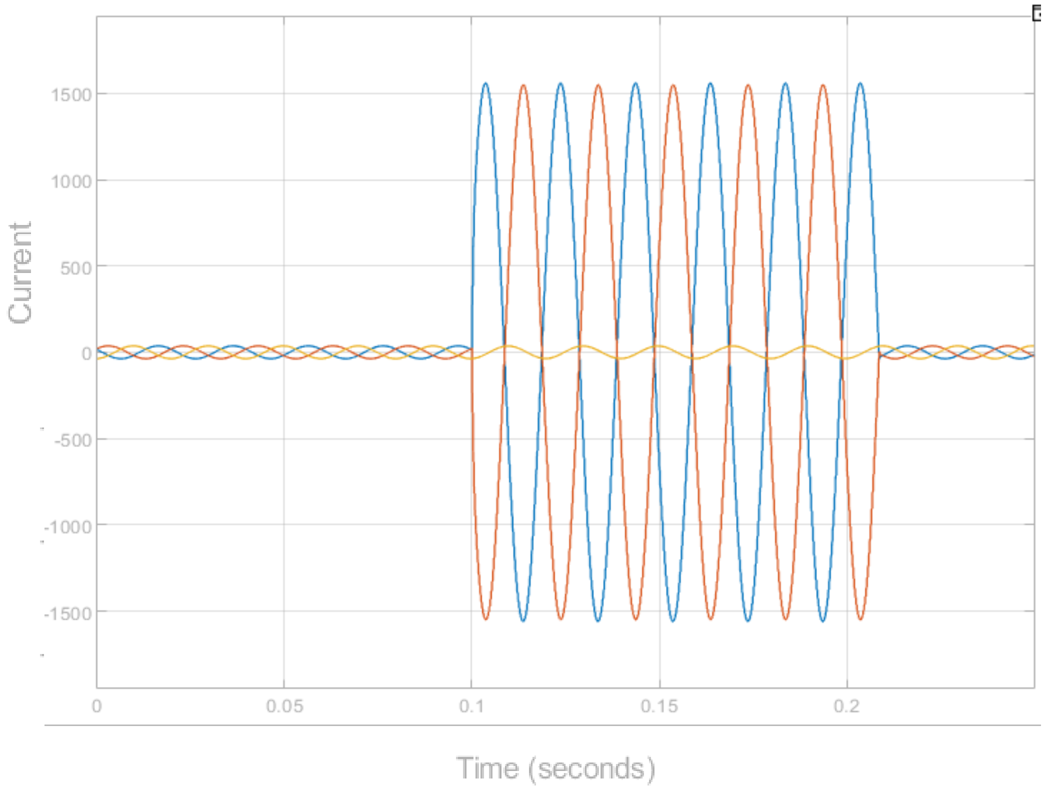

Fig 4.18. AB fault current on remote side of OHL.

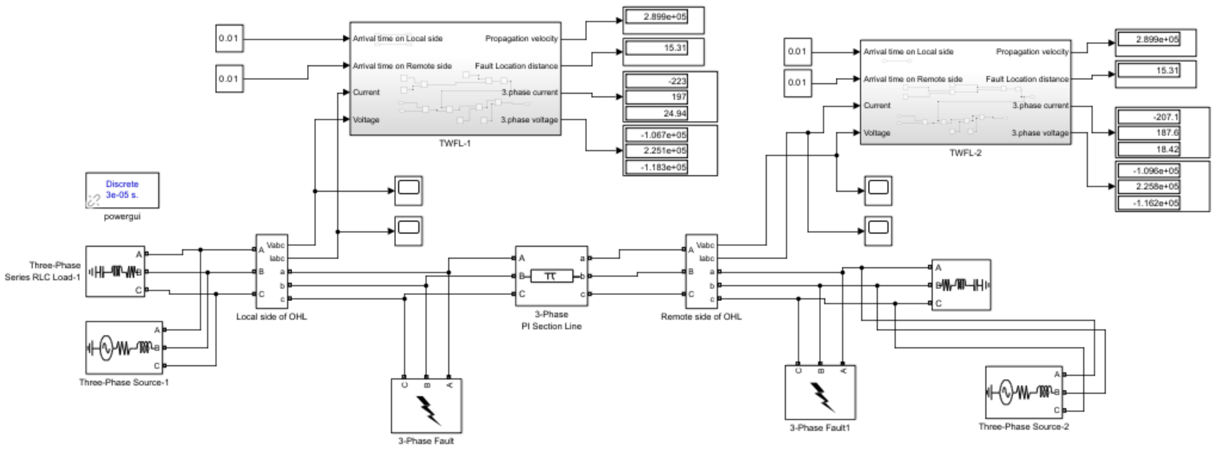

Fig. 4.19. AB fault on the transmission line was located at 15.61 km using the travelling wave model.

4.5. Three-phase (ABC) fault results

The voltage waveform of a simulated three-phase ABC fault is shown in Fig. 41 and Fig. 42. It can be observed that when the fault occurs, at approximately 100 milliseconds, the voltage magnitude of all phases falls to zero. When the fault is cleared at 200 milliseconds, the voltage across the phases ABC goes back to its pre-fault condition, reaching a high value of 2.7 pu, as it was initially operating before the fault.

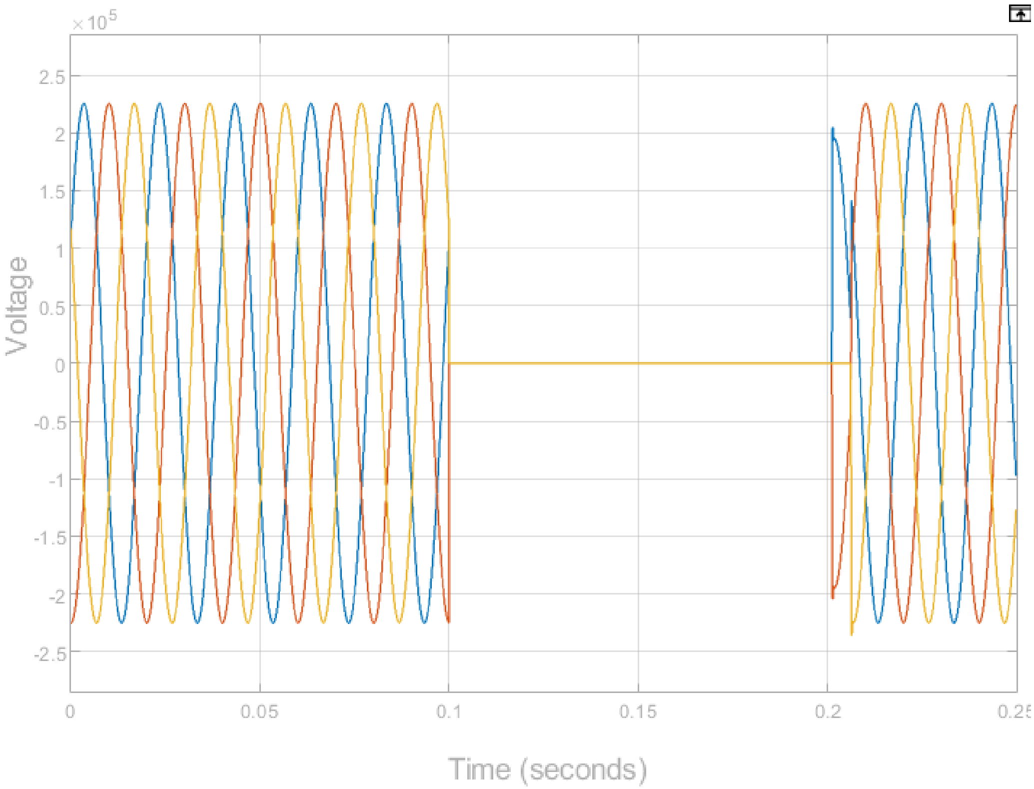

Fig 4.20. ABC fault voltage on local side of OHL.

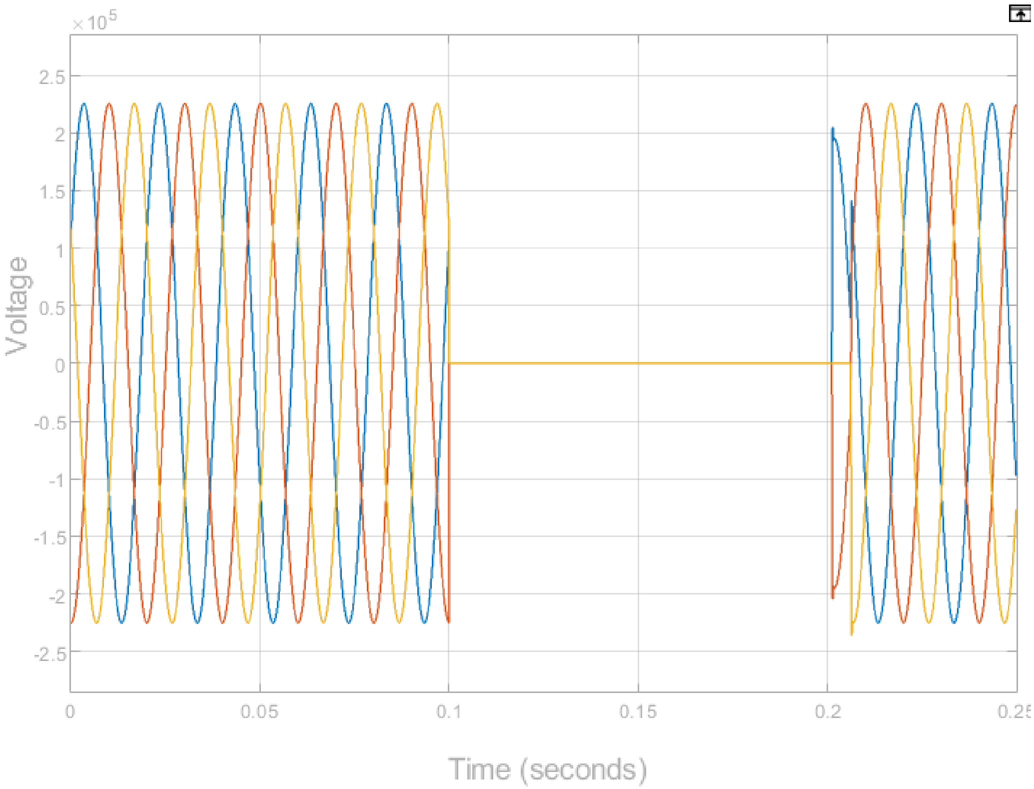

Fig 4.21. ABC fault voltage on remote side of OHL.

On the transmission line, the simulated three-phase ABC faults started at 100 ms and ended at 200 ms. Fig. 44 and Fig. 45 show the result of the current magnitude during the three-phase ABC fault: it can be seen that when the fault occurred at 100 milliseconds, the current magnitudes in all three phases ABC increased to approximately 6000 A. The waveform of the current at 200 milliseconds returns to its initial zero-point, after which it follows the same pattern until the clearing of the fault.

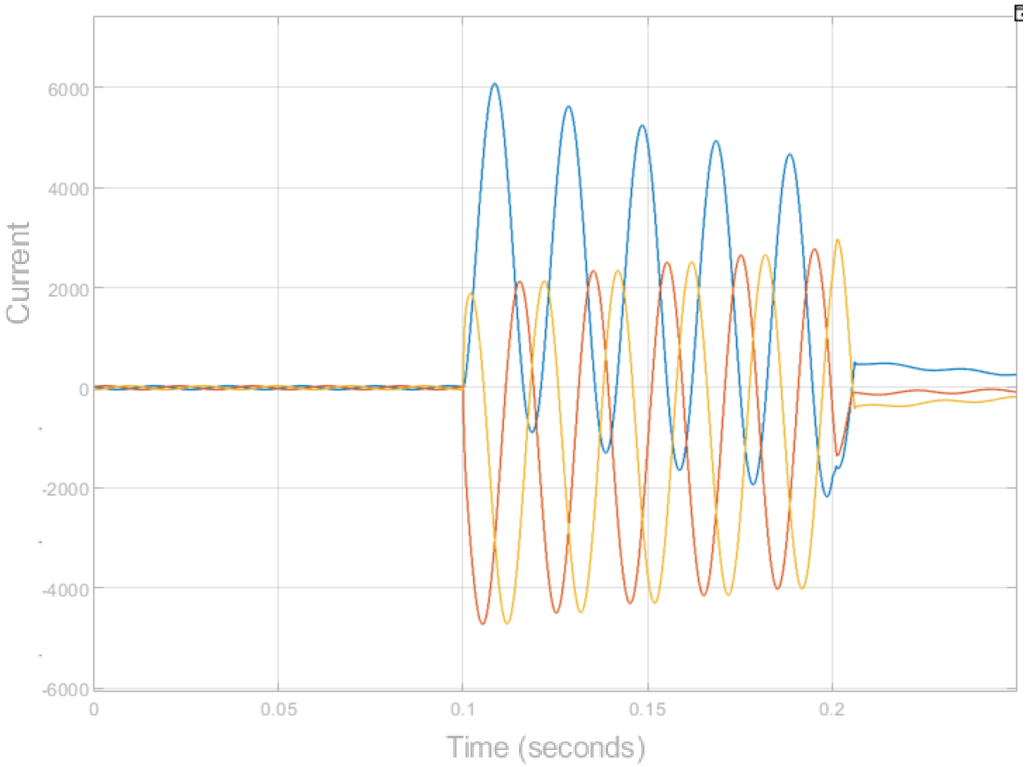

Fig 4.22. ABC fault current on local side of OHL.

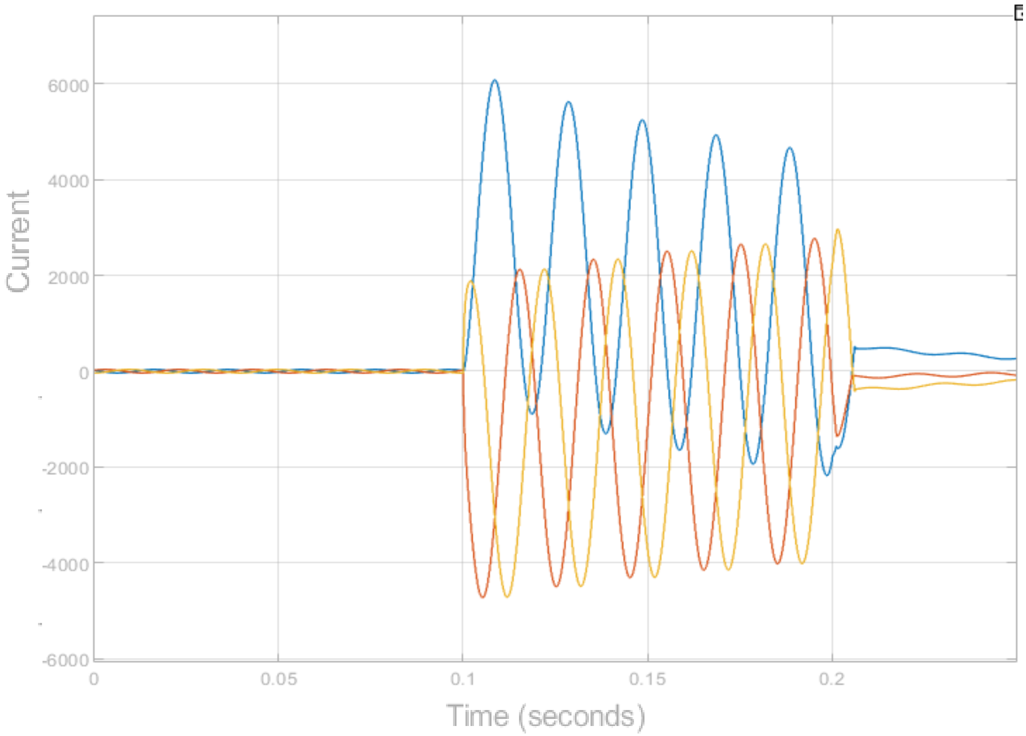

Fig 4.23. ABC fault current on remote side of OHL.

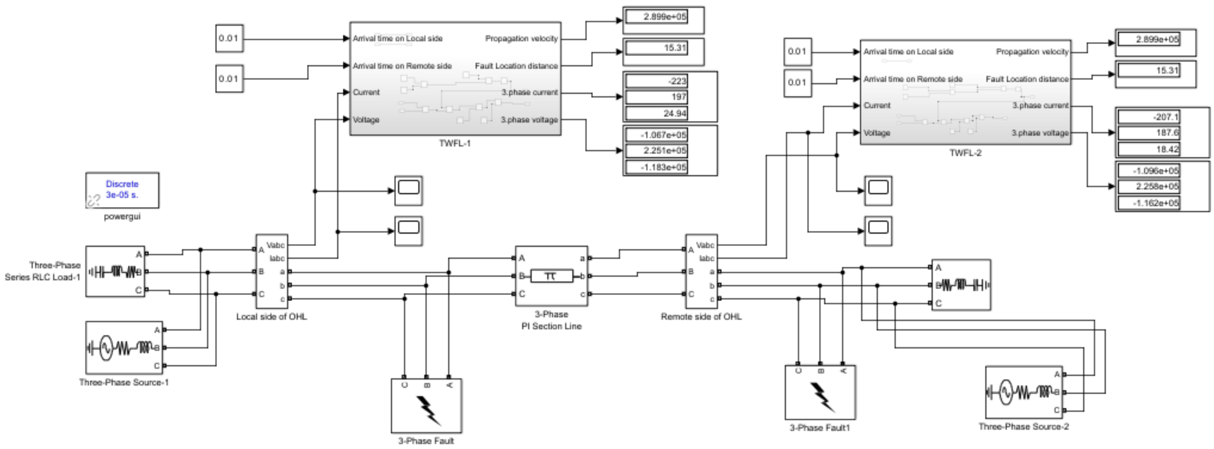

Fig. 4.24. ABC fault on the transmission line was located at 15.61 km using the travelling wave model.

CHAPTER FIVE:
DISCUSSION AND CONCLUSIONS

5.1 Results and Conclusion:

This project focused on fault location on a 220 kV overhead transmission line using the traveling wave method. Extensive modeling and simulation were performed in MATLAB/Simulink. It was shown that with the traveling wave approach, fault location could be attained with very high accuracy and well-reproducible results, avoiding most of the pitfalls common with conventional impedance-based techniques for fault location.

The simulation model consisted of a distributed parameter line representation, fault scenarios that simulated reality as closely as possible, and a TWFL subsystem capable of calculating wave propagation velocity and fault distance based on the time difference between wavefront arrivals at both terminals of the line. The simulation results as a whole confirmed both the theoretical basis and advantages of the traveling wave method for fault location applications.

Pre-Fault Conditions

Under normal, fault-free conditions, the system displayed stable and sinusoidal voltage and current waveforms at both the local and remote terminals. The magnitude of each phase voltage was about 2.2×10^5 V, and the current magnitude was around 90 A under steady state and with no disturbance. These pre-fault simulations were carried out to validate the correctness of the line and source modeling in the Simulink environment.

Single Line-to-Ground (A–G) Fault

When a single line-to-ground fault was applied to phase A, the corresponding voltage dropped abruptly to zero, while the voltage of the healthy phases decreased only slightly. The current in the faulty phase surged to about 1500 A, reflecting the sudden increase in flow of fault current. This fault was detected by the TWFL subsystem and the calculated distance from the local terminal was 15.61 km, which reflected the accuracy of the two-ended time-difference measurement method.

Double Line-to-Ground (AB–G) Fault

In case of a double line-to-ground fault between phases A, B, and ground, voltage collapse in both faulted phases occurs with increased magnitudes of current up to 1500 A. The voltage of the healthy phase C shows a momentary spike due to system imbalance. TWFL correctly located the fault at a distance of 15.61 km, the same result as that obtained for the single line-to-ground fault, and again confirms that the accuracy of this method does not depend on the fault type.

Line-to-Line (AB) Fault

In the case of a line-to-line fault between phases A and B, the voltages of the two faulty phases dropped to about 0.8×10^5 V, while the voltage of the healthy phase was kept constant. The respective currents increased to around 1500 A during the fault period. Again, under these conditions, the TWFL estimated the fault location as 15.61 km, proving the model's robustness and coherence for different fault types.

Three-Phase (ABC) Fault

The most severe fault condition that was simulated was the ABC three-phase short circuit, which caused all the phase voltages to collapse almost to zero while currents in each phase surged to around 6000 A. After the fault clearing, the system resumed the pre-fault steady-state waveform. The TWFL system estimated the same fault distance of 15.61 km, thereby validating the accuracy of the model even under symmetrical and high-current fault conditions.

Conclusion

The accuracy, speed, and reliability of a travelling wave method for fault location in an extra-high-voltage transmission system are clearly demonstrated from the results obtained. Indeed, the principle of dependence upon the time of propagation of electromagnetic waves and not upon line impedance or steady-state phasor parameters makes the method practically insensitive to such influences as fault resistance, system load, or network configuration.

The consistency in the results from all fault types justifies the robustness of the proposed method. Location accuracy within a few hundred metres, achieved in this way, is far beyond the kilometer-scale errors of impedance-based systems, normally caused by variations of fault resistance and line loading. Moreover, the method operates within a sub-millisecond time frame, making it ideal for real-time fault detection and system restoration.

The research also indicated practical limitations in applying the method on a real power system. It therefore requires high-speed sampling in the MHz range and precise GPS-based synchronization, which sets very high hardware and cost requirements. Inaccuracies in wavefront detection may be introduced by noise in the signal, reflections at discontinuities, and attenuation in long lines. These need to be addressed by advanced filtering, signal processing, and fault interpretation algorithms using intelligent methods.

In conclusion, this research has been able to establish the efficiency and validity of the traveling wave method in finding faults on a 220 kV overhead transmission line. The conclusions derived from this research are summarized below:

High Accuracy: For all fault types, the traveling wave approach located faults at 15.61 km from the local terminal, further confirming that the method provides sub-span-level precision.

Speed and Reliability: Because the method is based on a time-of-arrival approach of the first wavefronts, almost instantaneous fault location is possible. Therefore, faster fault isolation and system recovery are possible. The results of the TWFL subsystem presented for a single line-to-ground, double line-to-ground, line-to-line, and three-phase fault have confirmed robustness and universality, as fault-type independence holds.

The improvement in grid reliability: it is because many of these techniques can reduce the outage duration considerably, thereby increasing the operational efficiency and hence the overall reliability and resilience of high-voltage power networks.

Implementation Challenges: Very high-frequency data acquisition systems, highly accurate synchronization, and strong filtering mechanisms to remove noisy signals and reflections are needed..

5.2 Future research:

Future studies shall focus on integrating a traveling wave approach with machine learning and hybrid impedance-wave methods to realize higher accuracy, automatic wavefront recognition, and adaptive fault location under variable network conditions. It confirms again that a traveling wave-based method is a major development in the technology of fault location in power systems, helping upgrade electric grids and allowing faster, more reliable, and smarter management of faults within high-voltage transmission systems.

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