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Fault Detection and Identification in the Nkalagu to Enugu 132kV Power Transmission Line

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ABSTRACT: *This study presents a comprehensive evaluation of fault detection and location techniques applied to the Nkalagu–Enugu 132 kV transmission line, a critical infrastructure component within Nigeria's southeastern power grid. Given the line's significance in ensuring uninterrupted power delivery to urban and industrial zones, timely and accurate fault diagnosis is imperative. The investigation begins with an overview of conventional methods—such as impedance-based and symmetrical component analyses—highlighting their limitations in complex or high-resistance fault conditions. To overcome these shortcomings, advanced approaches including the Takagi method, current differential protection and wavelet-based transient analysis were examined through simulations using MATLAB/Simulink. A realistic digital twin of the 38.5 km transmission corridor was developed using π-model line representation and actual system parameters sourced from the Transmission Company of Nigeria (TCN). Fault scenarios were introduced across varying segments, and detection accuracy was evaluated under different fault resistances. The simulation results detect three phase (ABC) fault occurred at a distance point of 14.90km away from Bus B terminal, with a fault current 0.05pu and fault voltage of 0.051pu, also cleared the faults at 0.071sec, corresponding with the fault distance respectively, with minimal error margin, even under varying fault resistance and inception angles with errors consistently below 0.4%, affirming the robustness of the traveling wave-based model. Furthermore, the study confirms the influence of environmental and topographical factors on location precision, particularly over longer line segments. The findings advocate for the adoption of adaptive, intelligent protection schemes to bolster system resilience, minimize downtime, and support the evolving demands of Nigeria's power transmission infrastructure.*

Keyword: Fault detection, Fault identification, Transmission line, Impedance method, Nkalagu–Enugu, MATLAB/Simulink.

INTRODUCTION

The Nkalagu–Enugu 132 kV power transmission line is a critical segment of Nigeria's southeastern electricity grid, connecting the Nkalagu substation in Ebonyi State to the New Haven substation in Enugu State. This line serves as a vital conduit for bulk power delivery to the region, facilitating industrial activities and urban electrification. However, the line is susceptible to various fault conditions, including single-line-to-ground (SLG), line-to-line (LL), and three-phase faults, which can lead to significant power outages and economic losses (IIoh et.al.2022).

Fault detection and identification are essential for minimizing downtime and ensuring the reliability of the power supply. Traditional methods, such as impedance-based fault location techniques, rely on voltage and current measurements at one or both ends of the transmission line to estimate the fault's location (Razi-Kazemi et al., 2018). While effective, these methods can be influenced by factors such as fault resistance and line parameters, leading to inaccuracies in fault location estimation. (Shahabodin et.al. 2021) More advanced techniques, including traveling wave-based methods, utilize high-frequency signals generated by faults to determine their location These methods offer high accuracy and fast response times but require specialized equipment and may be sensitive to noise and signal attenuation over long distances (Jamil et al., 2021).

Recent advancements in artificial intelligence (AI) and machine learning (ML) have introduced new approaches to fault detection and location identification. AI-based methods can analyze complex patterns in electrical parameters to detect and classify faults with high accuracy. For instance, studies have demonstrated the application of artificial neural networks (ANNs) for fault detection and classification on Nigerian transmission lines, achieving high accuracy rates in fault location estimation.

This paper aims to evaluate and compare various fault detection and identification techniques applied to the Nkalagu–Enugu 132 kV transmission line. By simulating different fault scenarios and analyzing the performance of each method, this study seeks to identify the most effective approach for rapid and accurate fault location, thereby enhancing the reliability and efficiency of the power transmission system in southeastern Nigeria.

2.0 Overview of the Nkalagu–Enugu 132 kV Transmission Line

The Nkalagu–Enugu 132 kV transmission line is a critical segment of Nigeria's southeastern electricity transmission network, playing a pivotal role in the delivery of high-voltage power from the New Haven 330/132 kV substation in Enugu to the Nkalagu 132/33 kV substation in Ebonyi State. This line serves as a critical link in the Transmission Company of Nigeria's (TCN) network, supporting the distribution of electricity to key urban and industrial areas, including Enugu metropolis, Nsukka, Oji River, Nkalagu, and Abakaliki.

2.1 Technical Specifications and Infrastructure

The Nkalagu–Enugu line spans approximately 38.5 kilometers, transmitting power across a diverse geographical corridor that includes urban, semi-rural, and forested zones. It operates at a nominal voltage of 132 kilovolts (kV), with the New Haven substation stepping down the voltage from 330 kV to 132 kV. The Nkalagu substation, located in the Ishielu Local Government Area of Ebonyi State, serves as a critical node in the regional distribution network. In recent years, significant investments have been made to enhance the capacity and reliability of the Nkalagu to Enugu transmission corridor. In December 2023, TCN commissioned a 150 MVA 330/132 kV power transformer at the New Haven substation, augmenting the overall wheeling capacity and addressing previous load limitations in the Enugu Sub-Region of the Enugu Electricity Distribution Company (EEDC) (TCN, 2023). According to Eneh et al. (2024), this line is one of the primary feeders supplying power to industrial hubs and residential areas in Ebonyi and Enugu States, supporting both base and peak load demands in the region.

2.2 Challenges and Protection Strategies

Despite these infrastructural advancements, the Nkalagu to Enugu transmission line faces several operational challenges. The Nkalagu–Enugu 132 kV transmission line passes through a variety of geographical and environmental landscapes along its 38.5 km route, including urban, rural, and forested areas, which can influence fault occurrence and detection. Additionally, environmental factors such as vegetation growth and lightning strikes, as well as infrastructural issues like aging equipment and inadequate protection schemes, contribute to the vulnerability of the transmission line (TCN, 2023). To address these challenges, research has focused on improving

fault detection and protection strategies. A study by Eneh et al. (2024) investigated the application of a genetic-trained adaptive relay scheme to enhance the protection of the New Haven–Nkalagu 132 kV transmission network. The findings indicated a 26.43% reduction in tripping times and a 41.78% increase in current tap settings, demonstrating the potential of adaptive protection schemes in improving system reliability.

3.0 Fault Detection and Identification

The detection and identification of faults on the Nkalagu–Enugu 132 kV transmission line is critical for ensuring operational continuity, system stability, and minimizing downtime. This section outlines the analytical techniques applied to detect, identify, and locate faults using simulated current and voltage signals based on real-world system parameters. The methods adopted aim to replicate actual fault behaviors observed on this corridor and evaluate the suitability of different protection strategies. For this study, Fault detection is the initial step in power system protection, triggered when the system observes a deviation from normal operational conditions, it's based on real-time monitoring of voltage and current magnitudes, phase relationships, and zero-sequence components.

(a) Current Differential Protection: For internal fault discrimination, the difference in currents from both ends is computed as:

$$I_{diff} = I_{Enugu} - I_{Nkalagu} \quad (1)$$

A trip is initiated when $I_{diff} > I_{set}$ where I_{set} is a secure threshold accounting for measurement error and CT mismatch. This method is highly sensitive and fast, especially for internal line faults. It was modeled assuming ideal communication between both substations. The differential approach
demonstrated improved sensitivity to faults with higher resistance and was less susceptible to power swings and load changes (Horowitz and Phadke, 2014).

(b) Symmetrical Component Analysis: Symmetrical component transformation was applied to three-phase voltage and current signals to detect unbalance conditions caused by faults:

- **Zero-sequence components (I_0, V_0)** are dominant in SLG and DLG faults.
- **Negative-sequence components (I_2, V_2)** indicate phase unbalance.
- Positive-sequence **(I_1, V_1)** Used to monitor the system's balanced component.

This method is essential for classifying the type of fault and understanding the extent of asymmetry. Sequence component analysis is fundamental in distinguishing symmetrical from asymmetrical faults and is widely used in protection relaying (Elmore, 2004).

(c) Impedance-Based Detection (Distance Protection): This method uses voltage and current measurements from a relay point (typically the sending or receiving end) to calculate the apparent impedance during a fault:

$$Z_{app} = \frac{V_{fault}}{I_{fault}} \quad (2)$$

If Z_{app} falls within a predefined zone of protection (Zone 1, Zone 2, etc.), the relay identifies the fault and issues a trip signal. Distance relays are versatile but prone to inaccuracies in the presence of arc resistance, evolving faults, or heavy loading conditions (Shahabodin et al., 2021). Additionally, line loading and mutual coupling can introduce errors in fault distance estimation.

(d) Takagi Method: This method improves fault location accuracy by incorporating pre-fault voltage and fault current information:

$$D = R_e\left(\frac{(V_f - V_{pre}).I_f^*}{|I_f|.Z_{line}}\right) \quad (3)$$

Where:

- V_f, I_f: fault voltage and current,
- Vpre: pre-fault voltage,
- ∗: complex conjugate

This method is less sensitive to fault resistance and provides better estimates for long lines like Nkalagu–Enugu. The Takagi method is effective for long-line fault location where arc resistance and load flow distort conventional impedance calculations (Jamil et al., 2021).

(e) Wavelet-Based Transient Analysis (Optional Enhancement): Using Discrete Wavelet Transform (DWT), high-frequency transients were analyzed to detect fault inception within the first 10 ms of occurrence. Signal energy spikes were monitored across decomposition levels to identify incipient or evolving faults. Wavelet transform is advantageous in capturing high-frequency transients not visible in steady-state analysis, improving sensitivity to high-resistance or evolving faults (Atuchukwu et al., 2023).

3.0 Methodology

3.1 Data Acquisition and Line Modelling: The methodology employed in this study combines field-based data gathering, substation reports, and collaboration with the Transmission Company of Nigeria (TCN), with analytical modelling to develop a realistic simulation framework for analyzing the fault behavior of the Nkalagu–Enugu 132 kV, 50Hz transmission line. The overall goal is to create a high-fidelity digital twin of the physical line that accurately reflects its electrical characteristics and operating conditions. The following data sets were obtained:

- **Line parameters**: Positive, negative, and zero-sequence impedances; conductor type (ACSR), length of the transmission line (38.5 km), and tower configurations.
- **Operational records**: SCADA logs of historical fault events (including fault currents, voltages, and relay actions).
- **Protection settings**: Relay characteristics and tripping logic currently implemented at the New Haven (Enugu) and Nkalagu substations.

3.2 Transmission Line Modelling

The Nkalagu to Enugu 132 kV line was modeled using the ***π*-model representation**, which is suitable for medium-length transmission lines. Considering a small segment of the transmission line of length *dx*, the parameters per unit length include resistance R, conductance G, inductance L, and capacitance C, as illustrated in Figure 1. These parameters were obtained from SCADA data, engineering reports from the Transmission Company of Nigeria (TCN), and IEEE Standard 738. For this segment, the line constants are *Rdx, Gdx, Ldx, and Cdx* respectively (Mohammad, 2013). The electric flux ψ and magnetic flux φ generated by the electromagnetic wave give rise to the instantaneous voltage u(x,t) and current i(x,t) along the line.

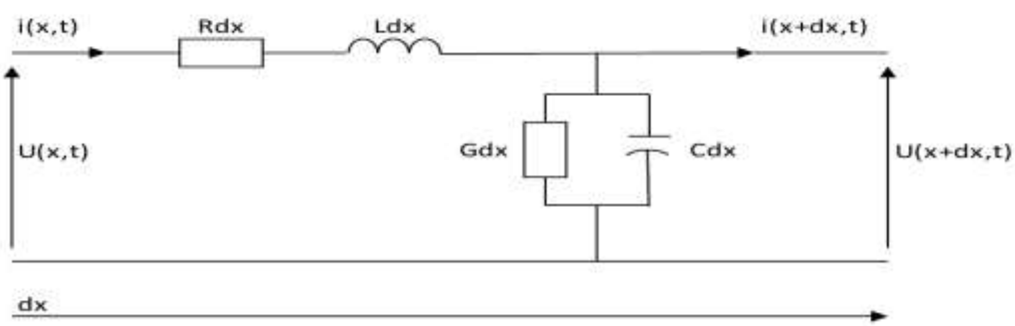

Figure 1 Single phase transmission line model (Wesley, 2019).

$$d\Psi(t) = u(x,t)Cdx \quad (4)$$

And

$$d\varphi(t) = i(x,t)Ldx \quad (5)$$

The voltage drops in the positive ***x***- direction over a small distance ***dx*** is Calculated as follows;

$$u(x,t) - u(x+dx,t) = du(x,t) =$$
$$-\frac{\partial u(x,t)}{\partial x}dx =$$

$$\left(R + L\frac{\partial}{\partial t}\right) i(x,t)dx \quad (6)$$

When dx is cancelled from both sides of equation (6), the voltage equation simplifies to:

$$\frac{\partial u(x,t)}{\partial x} = -L\frac{\partial i(x,t)}{\partial t} - Ri(x,t) \quad (7)$$

Similarly, applying Kirchhoff's current law for the current flowing through the conductance G and the charging current capacitor C gives;

$$i(x,t) - i(x + dx, t) = -di(x,t) = -\frac{\partial i(x,t)}{\partial x} = \left(G + C\frac{\partial}{\partial t}\right) e(x,t)dx \quad (8)$$

After canceling dx from both sides of equation (8), the current equation reduces to:

$$\frac{\partial i(x,t)}{\partial x} = -C\frac{\partial u(x,t)}{\partial t} - Gu(x,t) \quad (9)$$

The negative sign in this equation arises because, as the current and voltage waves propagate in the positive x-direction, the amplitudes of $i(x, t)$ and $u(x, t)$ decrease with increasing x. By substituting and differentiating once more with respect to x, the resulting second-order partial differential equations are obtained:

$$Z = R + \frac{\partial L(x,t)}{\partial t} \text{ and } Y = G + \frac{\partial C(x,t)}{\partial t} \quad (10)$$

$$\frac{\partial^2 i(x,t)}{\partial x^2} = -Y\frac{\partial u(x,t)}{\partial t} = YZi(x,t) = Y^2 i(x,t) \quad (11)$$

$$\frac{\partial^2 i(x,t)}{\partial x^2} = -Y\frac{\partial u(x,t)}{\partial t} = YZi(x,t) = Y^2 i(x,t) \quad (12)$$

In this equation, γ is a complex quantity known as the propagation constant, defined as:

$$\gamma = \sqrt{ZY} = \alpha + j\beta \quad (13)$$

Where, γ is a complex quantity known as the propagation constant; α is the attenuation constant, affecting the amplitude of the travelling wave; and β is the phase constant influencing the phase shift of the travelling wave (Baser, 2013).

3.3 Simulation Modelling

The model was developed and simulated using **MATLAB/Simulink Sim-Power Systems Toolbox**, with the following key considerations: Series Impedance Modelling were configured

using per-unit values of resistance (*R*) and inductive reactance (*X*), Shunt Capacitance Modelling was included to reflect the line's capacitive charging effect. This is crucial for capturing transient overvoltage behavior during fault simulations. Voltage sources and Load representing the 330/132 kV New Haven and 132/33 kV Nkalagu injection substations were modeled with their respective source impedances. Nominal loading conditions were applied at the receiving end to simulate real operating states. Circuit breakers, current transformers (CTs), potential transformers (PTs), and protective relays are modeled to simulate the full protection scheme while the line was divided into multiple segments to simulate faults at various locations (e.g., 5km, 10km, 15km, 20km, 25km, 30km and 35km from the Enugu end).

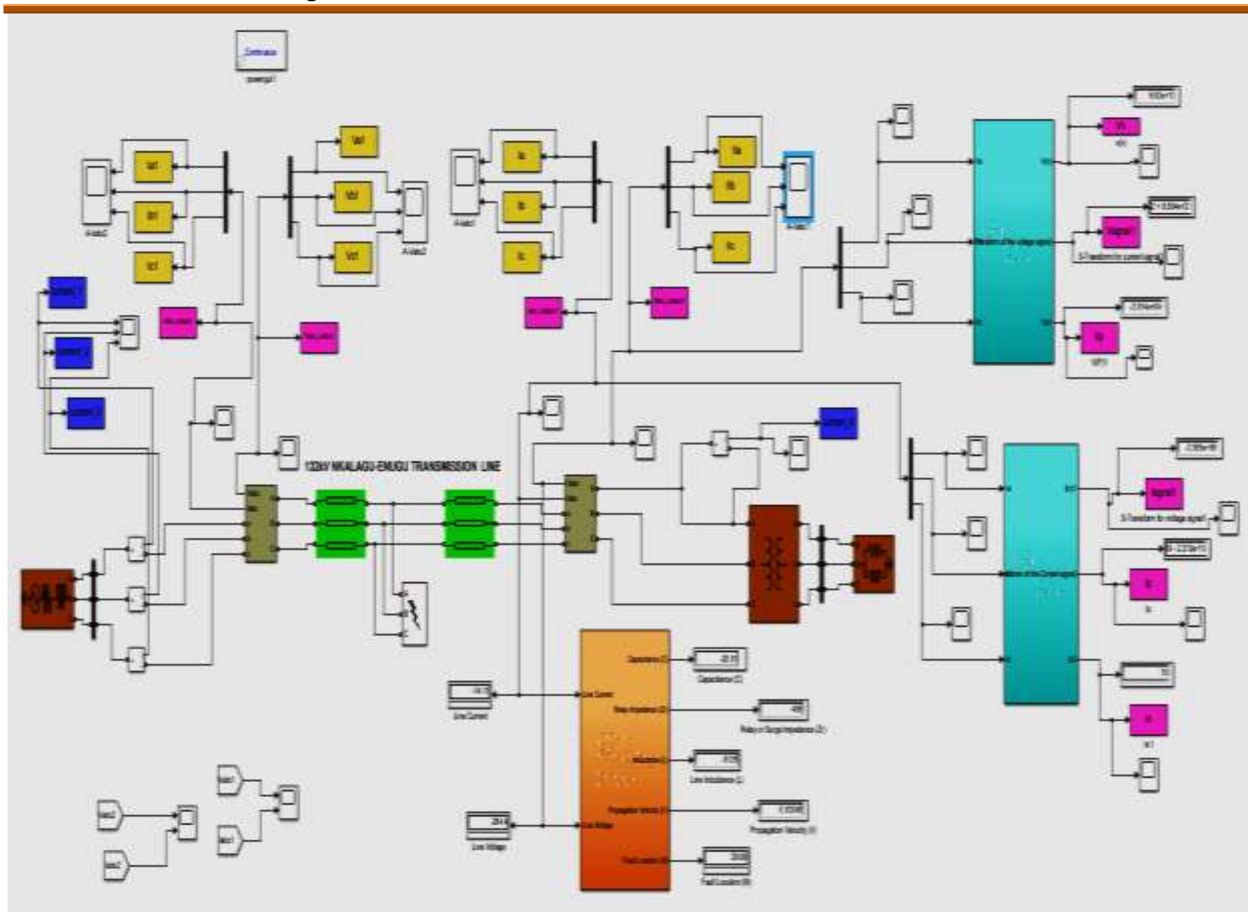

Figure 2: Simulink Model for Location of fault on Nkalagu-Enugu 132kV transmission line

V. RESULTS ANALYSIS

The simulation results for the Nkalagu to Enugu 132kV, 50Hz transmission line, which spans 38.5 km, are presented in this section. For analysis, the line is divided into segments of 5km each, resulting in seven possible fault locations. The MATLAB/Simulink model is employed to locate three-phase (ABC) fault distances along each 5km segment. The obtained results, along with their analysis, are discussed below.

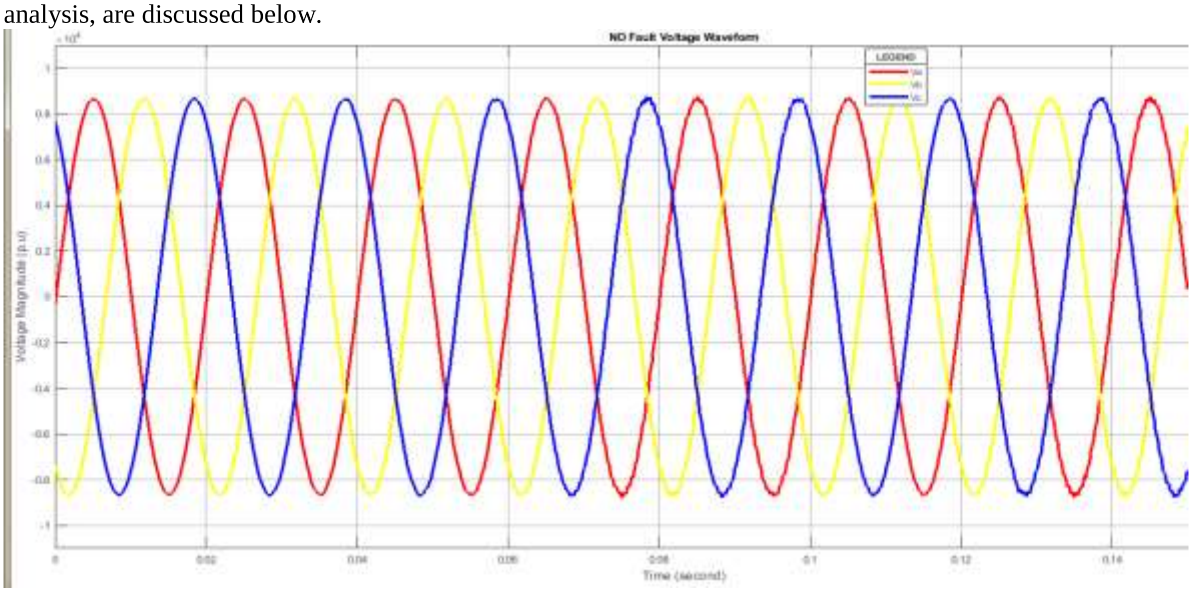

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Figure 3: Three Phase Pre-fault Voltage Waveform.

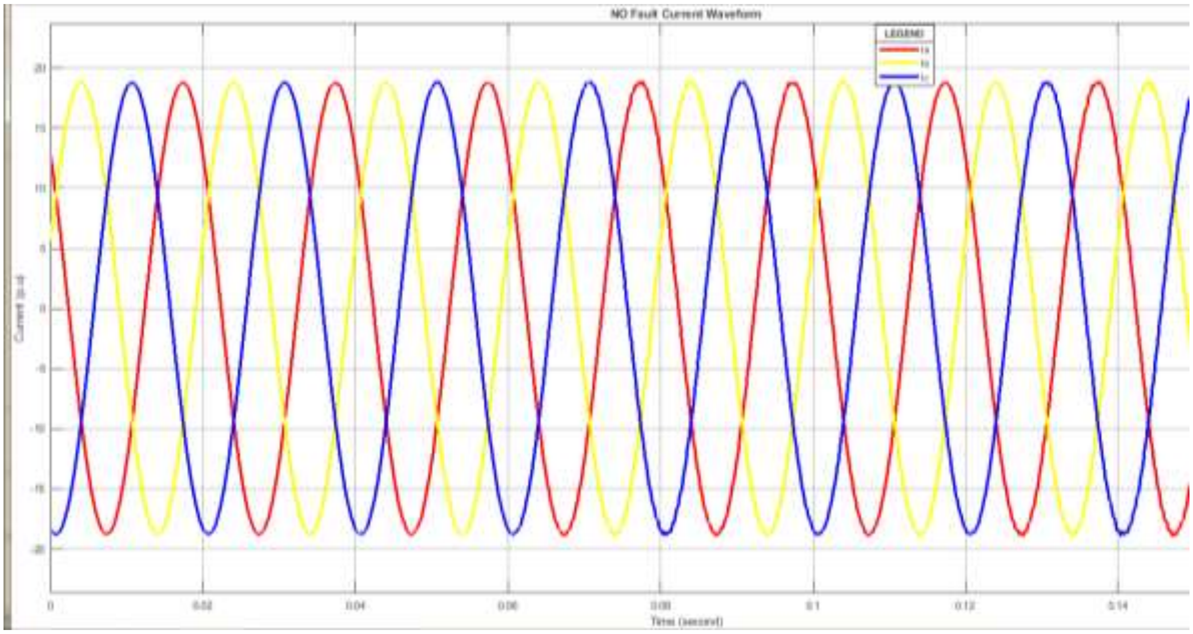

Figure 4: Three Phase Pre-fault Current Waveform.

Figures 3 and 4 illustrate the pre-fault voltage and fault current waveforms from the simulation of the system under normal, fault-free conditions. These waveforms, captured before any fault occurrence, show that the voltage and current for all three phases exhibit a sinusoidal shape, closely matching ideal sine waves. When no fault is present, both the magnitude and the Gaussian window length remain constant throughout the observation period.

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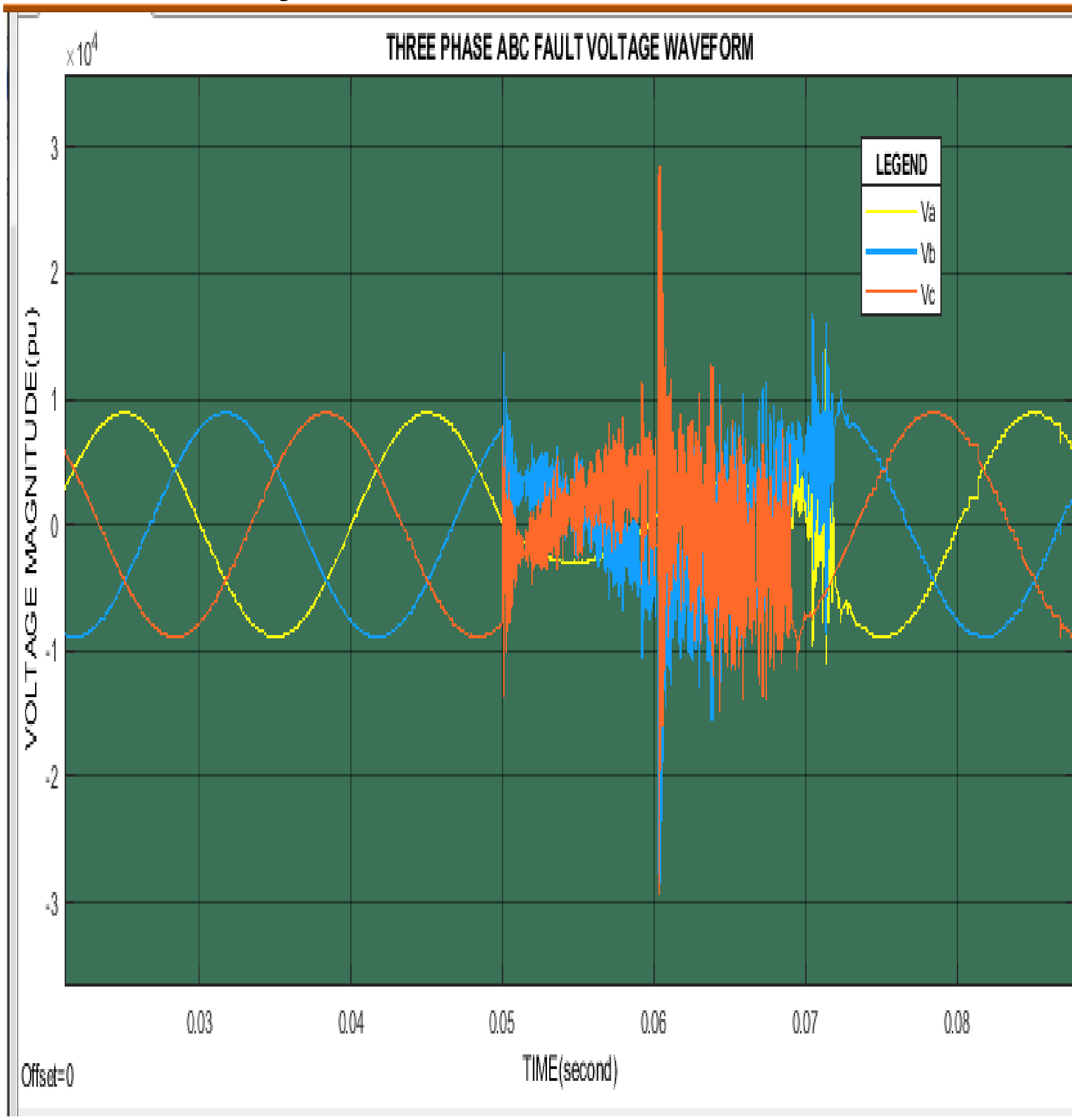

Figure 5: Three Phase ABC Fault Voltage Waveform

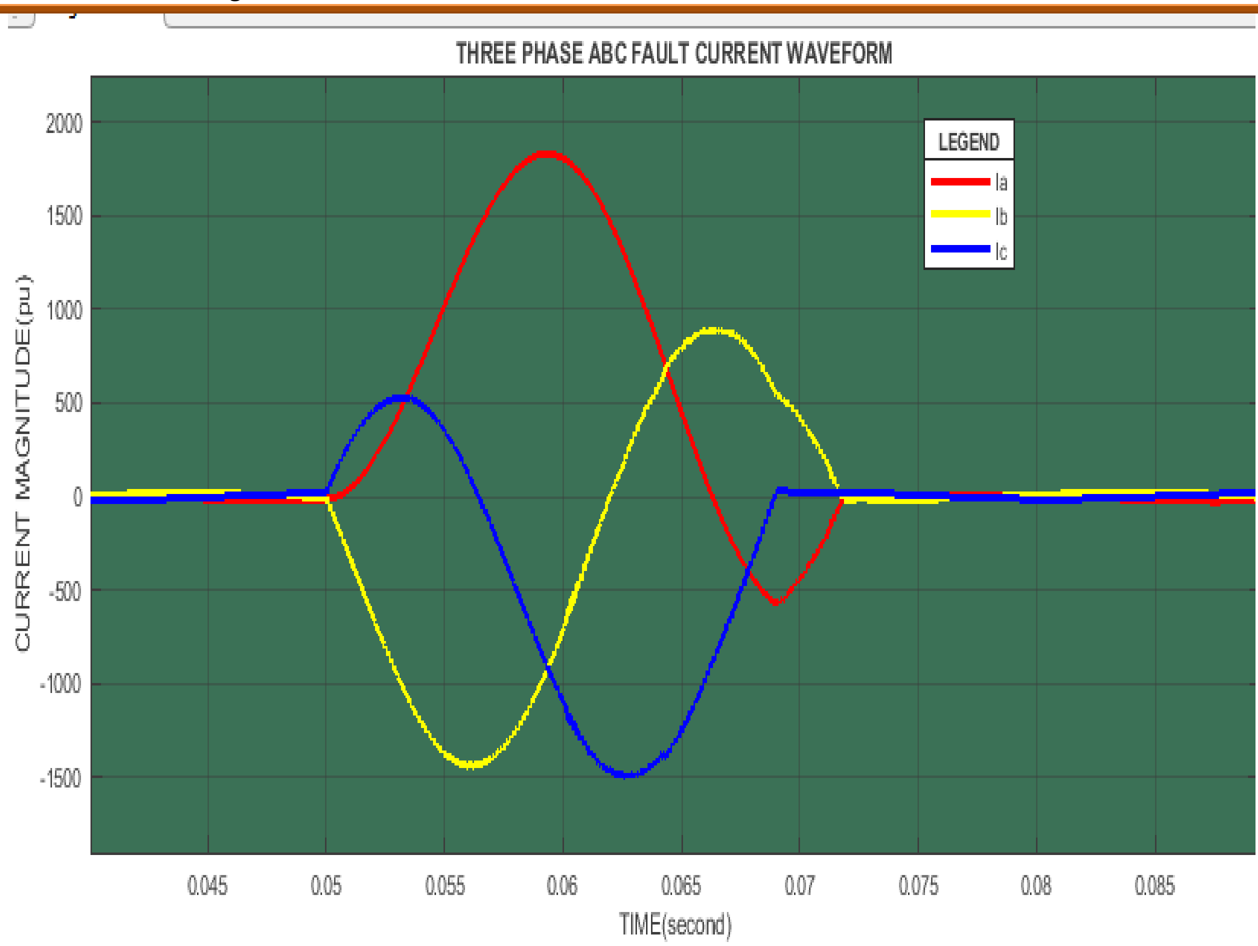

Figure 6: Three Phase ABC fault Current Waveform

A three-phase ABC fault was simulated, with the voltage waveform results shown in Figure 5. It is evident that at the fault occurrence around 0.05ms, the voltage magnitude of all three phases dropped to zero. When the fault was cleared at 0.072ms, the voltage magnitude of phases ABC rose back to approximately 2.5pu, which was the original pre-fault level. Similarly, three-phase ABC fault introduced on the transmission line, the current magnitude results are shown in Figure 6. The fault inception time occurred at 0.05ms near Bus B, with the current magnitudes of phases ABC increasing sharply to about 1.5×10^5pu. This elevated current level persisted until the fault was cleared at 0.12ms, after which the current waveform returned to its normal value of zero.

Table 1

Three-phase ABC fault					
Fault Distance (km)	**Fault Resistance (Ω)**	**Fault inception time (s)**	**Measuring Time**	**Calculated Fault Distance (km)**	**Fault Location Error %**
5	5	0.05	0.070	4.95	0.1
	10	0.04	0.071	4.89	0.2
	100	0.05	0.070	4.87	0.3
10	5	0.05	0.071	9.89	0.2
	10	0.05	0.070	9.95	0.1
	100	0.05	0.071	9.92	0.2
15	5	0.05	0.070	14.88	0.3
	10	0.05	0.070	14.90	0.2
	100	0.05	0.072	14.95	0.1

20	5	0.05	0.071	20.05	0.1
	10	0.05	0.072	19.86	0.3
	100	0.05	0.071	20.06	0.1
25	5	0.05	0.071	24.82	0.4
	10	0.05	0.070	24.89	0.2
	100	0.05	0.070	24.93	0.1
30	5	0.05	0.071	30.87	0.3
	10	0.05	0.071	30.93	0.1
	100	0.05	0.071	30.96	0.1
35	5	0.05	0.071	34.87	0.3
	10	0.05	0.071	34.87	0.3
	100	0.05	0.071	34.93	0.1

Table 1 presents the simulation results derived from the application of a traveling wave-based fault location model developed using MATLAB/Simulink, specifically applied to the 132 kV Nkalagu to Enugu transmission line. For clarity and conciseness, only the results corresponding to a two-three phase (ABC) fault are presented, as inclusion of all unsymmetrical fault cases would render the data excessively voluminous and complex to interpret. The data in Table 1 corresponds to the simulation output of the MATLAB/Simulink model depicted in Figure 5 and 6, which is configured to detect and identify symmetrical faults. The analysis indicates a direct correlation between line length and fault distance estimation, where an increase in transmission distance results in a proportional increase in estimated fault distance. This observed trend is attributed to topographical variations and the spatial change in the fault's inception point along the transmission corridor. These results align with established transmission line theory, which posits that shorter line segments exhibit greater stability and minimal impedance fluctuation due to limited disturbances. Conversely, longer lines are more susceptible to variations in impedance and signal propagation characteristics, as they are exposed to multiple external influences, including electromagnetic interference, line losses, fault symmetries, and environmental factors such as wind loading.

VI. Conclusion

The study of fault detection and identification on the Nkalagu–Enugu 132 kV transmission line has demonstrated the effectiveness of an integrated protection approach that combines conventional methods with modern intelligent techniques. Through the development and simulation of a digital twin model in MATLAB/Simulink, it was shown that while traditional impedance-based and symmetrical component methods provide reliable detection under ideal conditions, their accuracy diminishes significantly under high-resistance fault scenarios or complex line loading conditions. In contrast, current differential protection schemes proved more robust and sensitive, especially for internal faults, due to their direct measurement of current differences across line ends. The Takagi method further improved fault location accuracy by incorporating both pre-fault and fault conditions, showing reduced sensitivity to fault resistance.

The application of transient-based analysis, particularly through discrete wavelet transforms (DWT), enabled early detection of evolving and incipient faults by capturing high-frequency signal distortions—something traditional techniques often miss. Furthermore, the integration of AI/ML approaches presents a promising frontier, offering adaptive learning and pattern recognition capabilities that enhance fault classification and localization accuracy in real time.

Simulation results for various three-phase fault scenarios confirmed that fault location errors remained within a narrow margin (0.1–0.4 km), validating the model's precision. Notably, fault location error increased slightly with line length due to impedance variability and signal attenuation, confirming the theoretical expectations regarding wave propagation over long distances. Ultimately, the analysis underscores the need for a hybrid protection architecture that combines fast-acting traditional schemes with intelligent signal processing and AI-based analytics. Such a system would significantly enhance the reliability, responsiveness, and operational resilience of the Nkalagu–Enugu transmission corridor. These findings are not only critical for regional grid stability in southeastern Nigeria but also offer a scalable model for fault management across similar transmission systems in developing power networks.

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